Powering the internet of things

Yogesh Ramadass

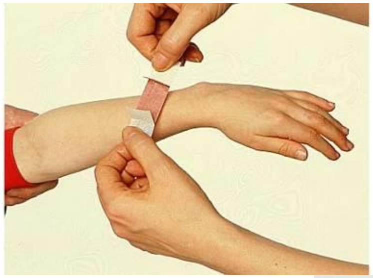
Texas Instruments

Trends in low-power electronics

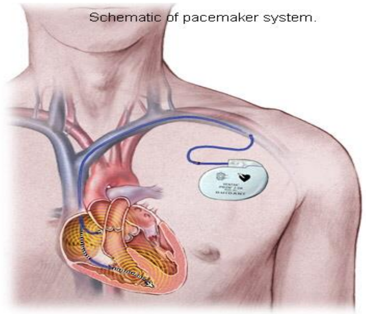
Increasing Energy Criticality

Portable Computers

Wearable Devices



Implantables



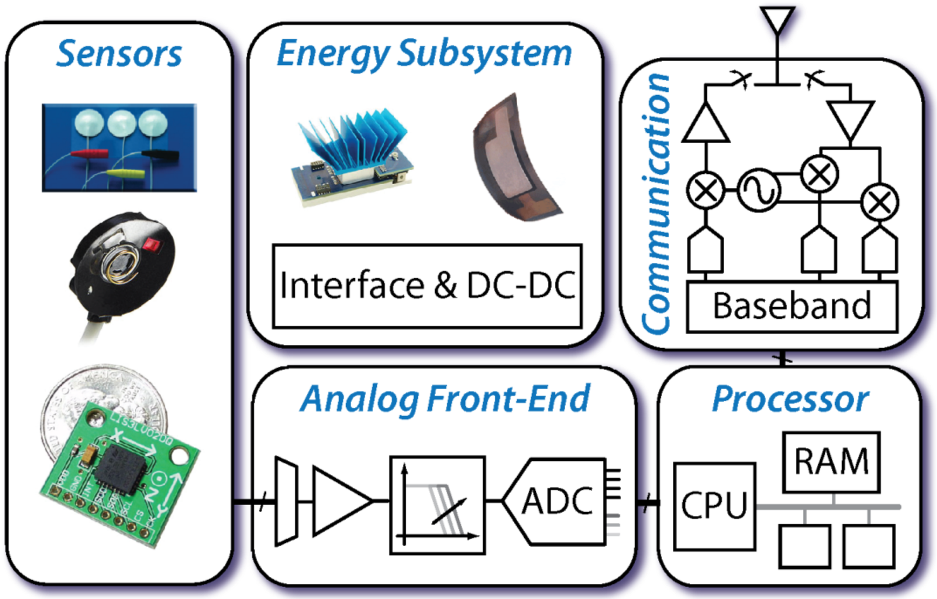
Handhelds

Sensor Networks

- Issues - Size, weight, operating lifetime
- Energy efficiency of IC's is crucial

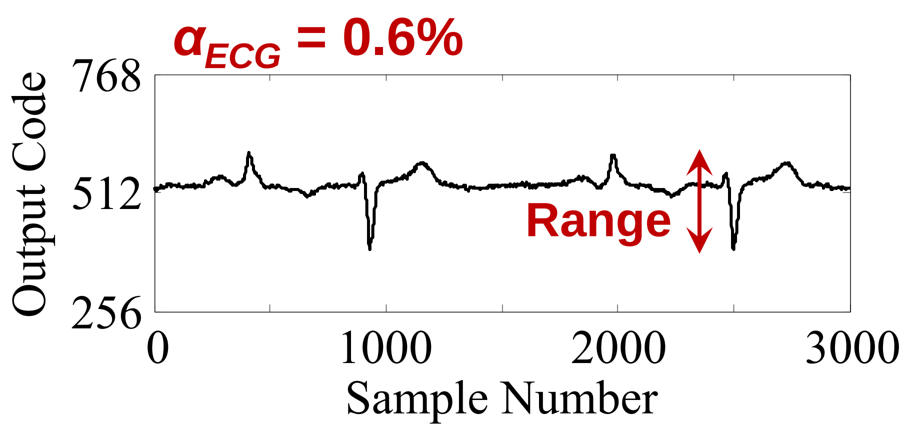
IoT Node for Monitoring

Component	Power	Comments
Inst. Amplifier [Verma, VLSI09]	3.5µW	1V V_{DD}, 1.3µVrms input referred noise
ADC [Yaul, ISSCC14]	3.7µW	1V V_{DD}, 450kS/s, 9.8ENOB
16b µ-cont [Kwong, ISSCC08]	2.72µW	0.5V V_{DD},128kb SRAM, 100kHz
Radio [CC 2550]	33.6mW (active)	3V V_{DD}, 2.4GHz, -12dBm P_{OUT}

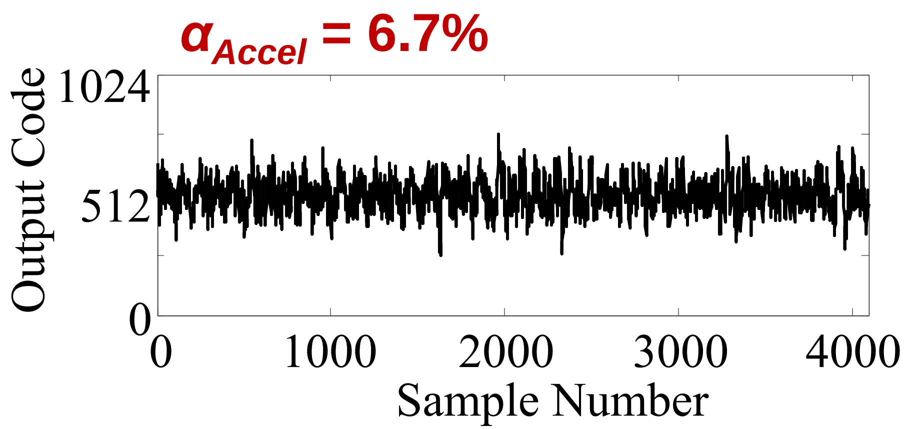


- Power consumption of building blocks steadily decreasing
- Low voltage operation, multi-cores, local processing of information, aggressive duty cycling

LSB-first SAR ADC for Low-Activity Signals



ECG Signal, 1 kS/s



Vibration Signal, 5 kS/s

Technology	0.18µm		
Unit Capacitor (fF)	72		
Supply Voltage (V)	1.0	0.6	0.5
Sample Rate (Hz)	450k	16k	4k
ENOB (bit)	9.82	9.73	9.55
Power (W)	3.7–13µ	47–170n	8.7–31n
FoM (fJ)	9.1–35	3.5–20	2.9–17

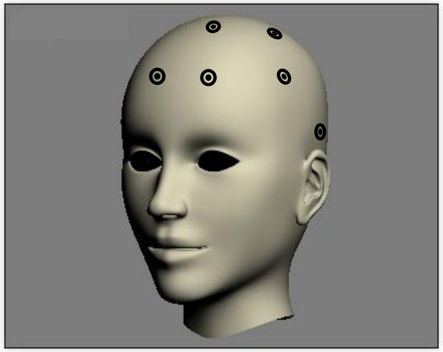
Range is given for best case (DC) and worst case (fullscale Nyquist sinusoid) inputs.

[F. Yaul, ISSCC 2014]

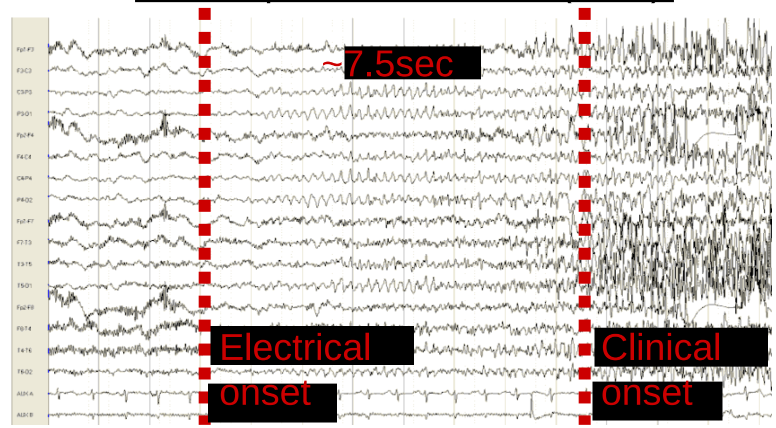
LSB-first predictive algorithm for reduced power

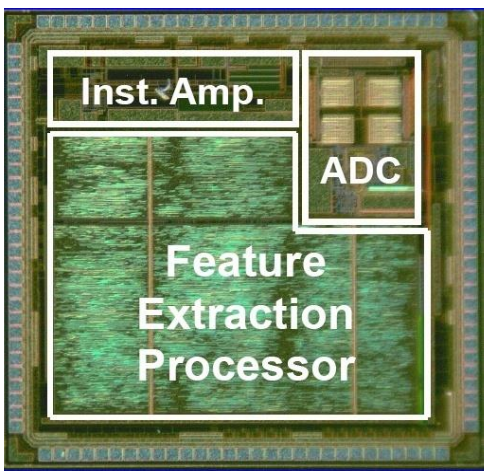
Reduced radio consumption

Epileptic Seizure Onset Detection



On-scalp Field Potentials (EEG):





	Conventional-Wireless EEG	Using Local Processing
Capture	**75 μW**	**75 μW**
Digital processing	**--**	**2 μW**
Radio	**1733 μW**	**43 μW**
Total	**1808 μW**	**120 μW**

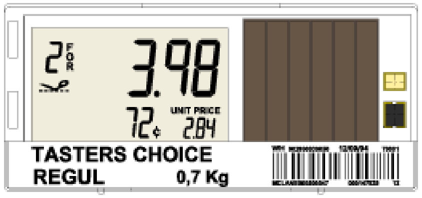
Computation vs. Communication Trade-off

[N. Verma, VLSI Circuits Symposium 2009]

Self-Powered Applications

Low data rate, low duty cycle, ultra-low power

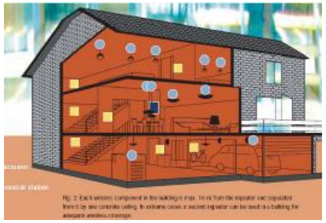
Solar Keyboard



Electronic Shelf Labels

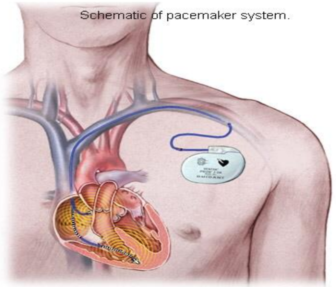
Self-powered switches

Convenience



Occupancy Sensor

Environmental Awareness



Implantables

Pipelines

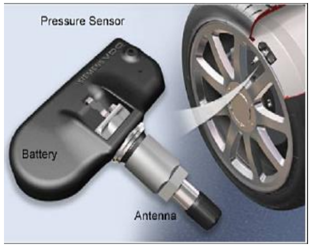
Oil Rig

Smoke Detector

Structural sensors

Hard to Reach

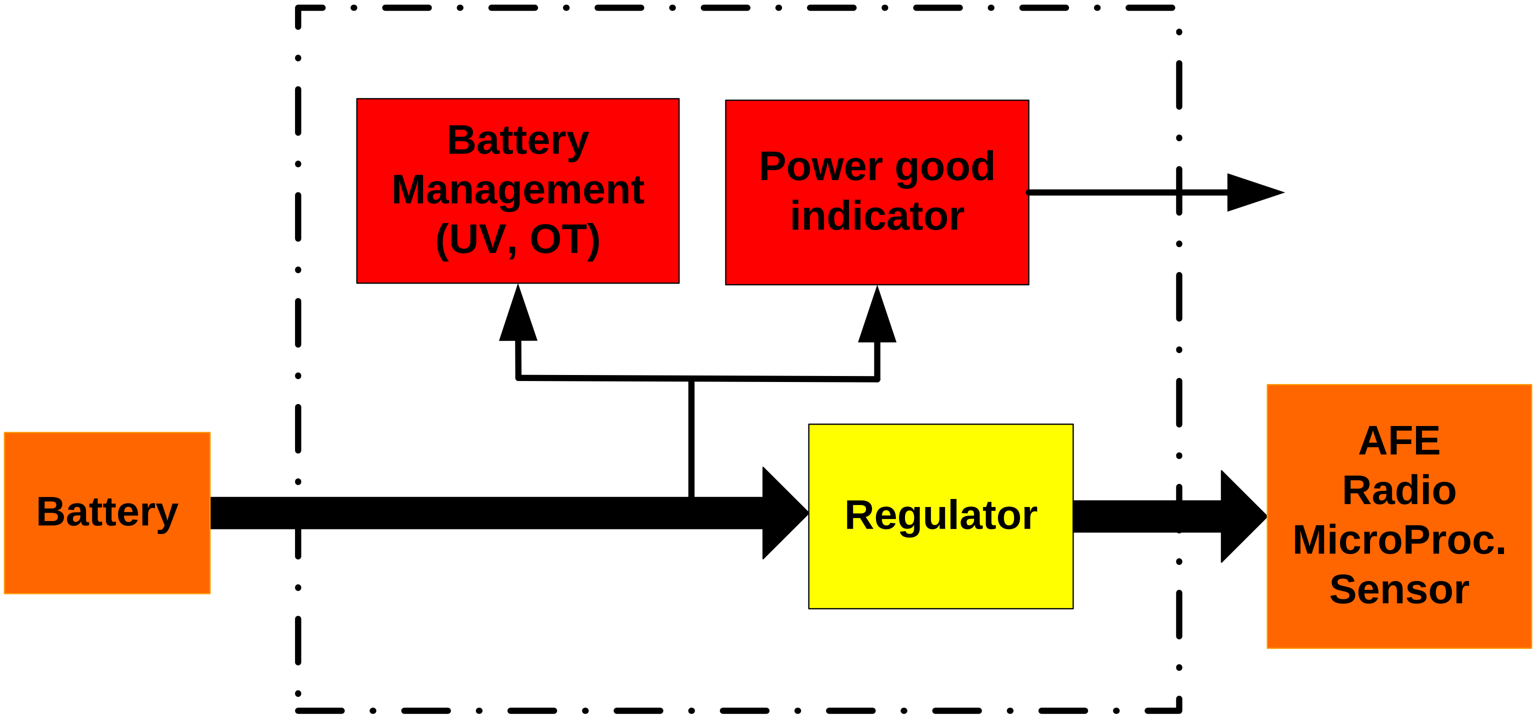
TPMS



Outline

- Energy Sources and Characteristics
  - Energy Harvesting System
  - Solar
  - Thermal
  - Vibration
- Energy Storage Options
- Energy Management Circuits
  - Chargers
  - DC/DC Converters
  - Battery Management
  - Peripherals
- Summary

Battery Operated System

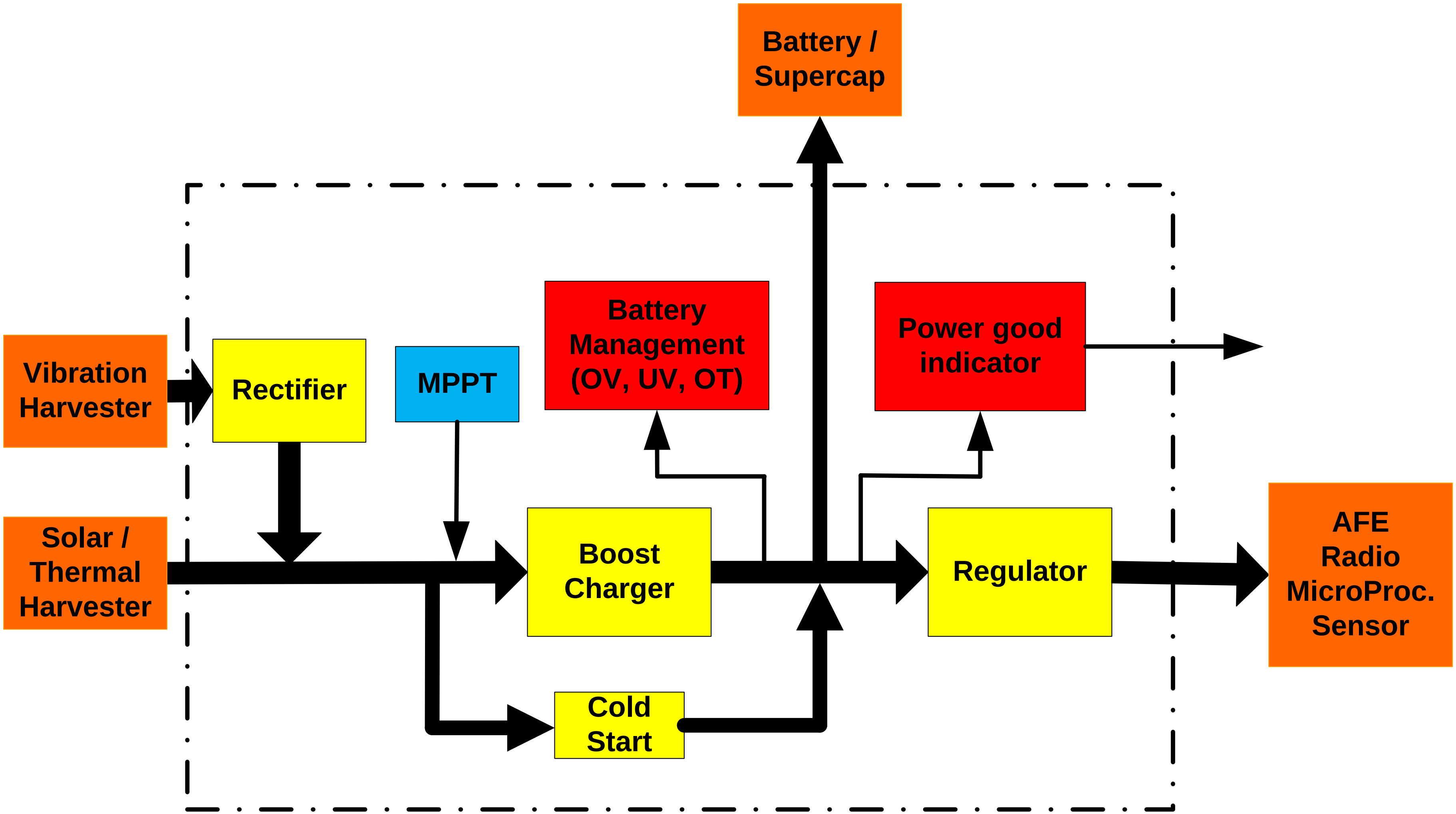


- Battery is an energy source
- System needs to be ON only when the load demands it

1cm^3 Li-ion → 2800J → 1year at 100µW

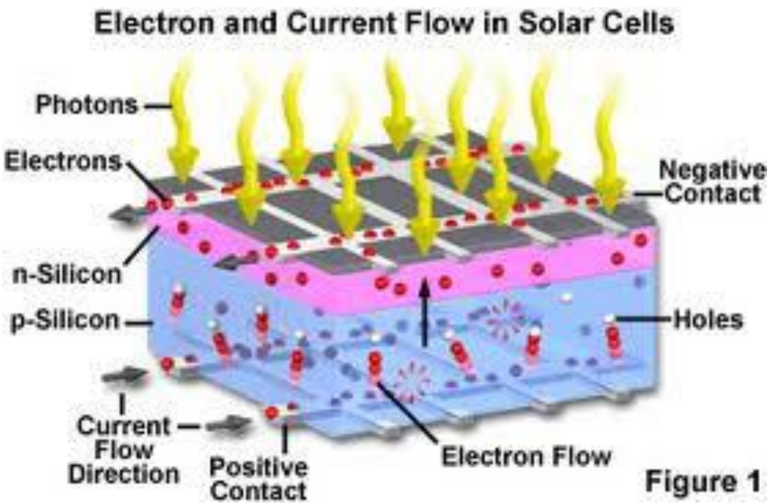
Self-powered solutions desirable

Energy Harvesting System

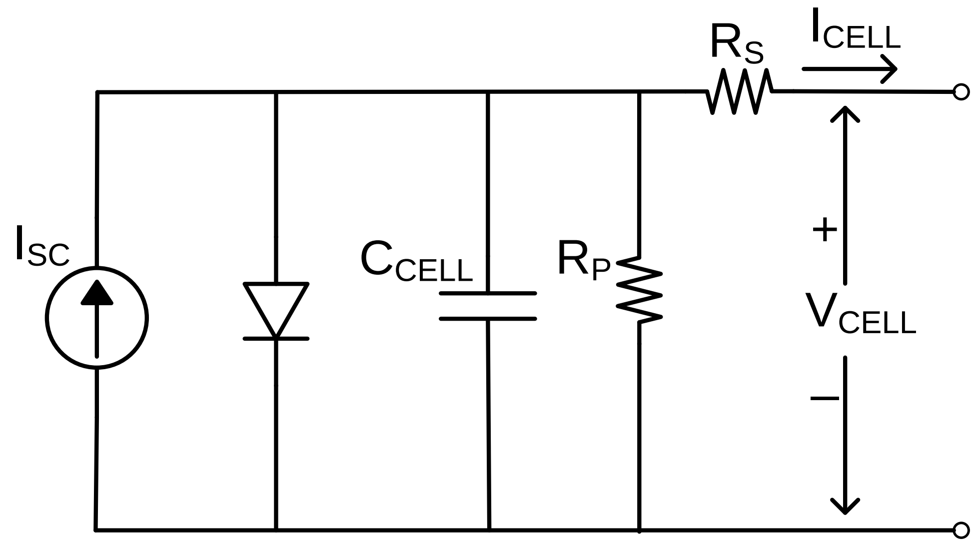


Energy harvesters are power sources

Harvesting Light Energy

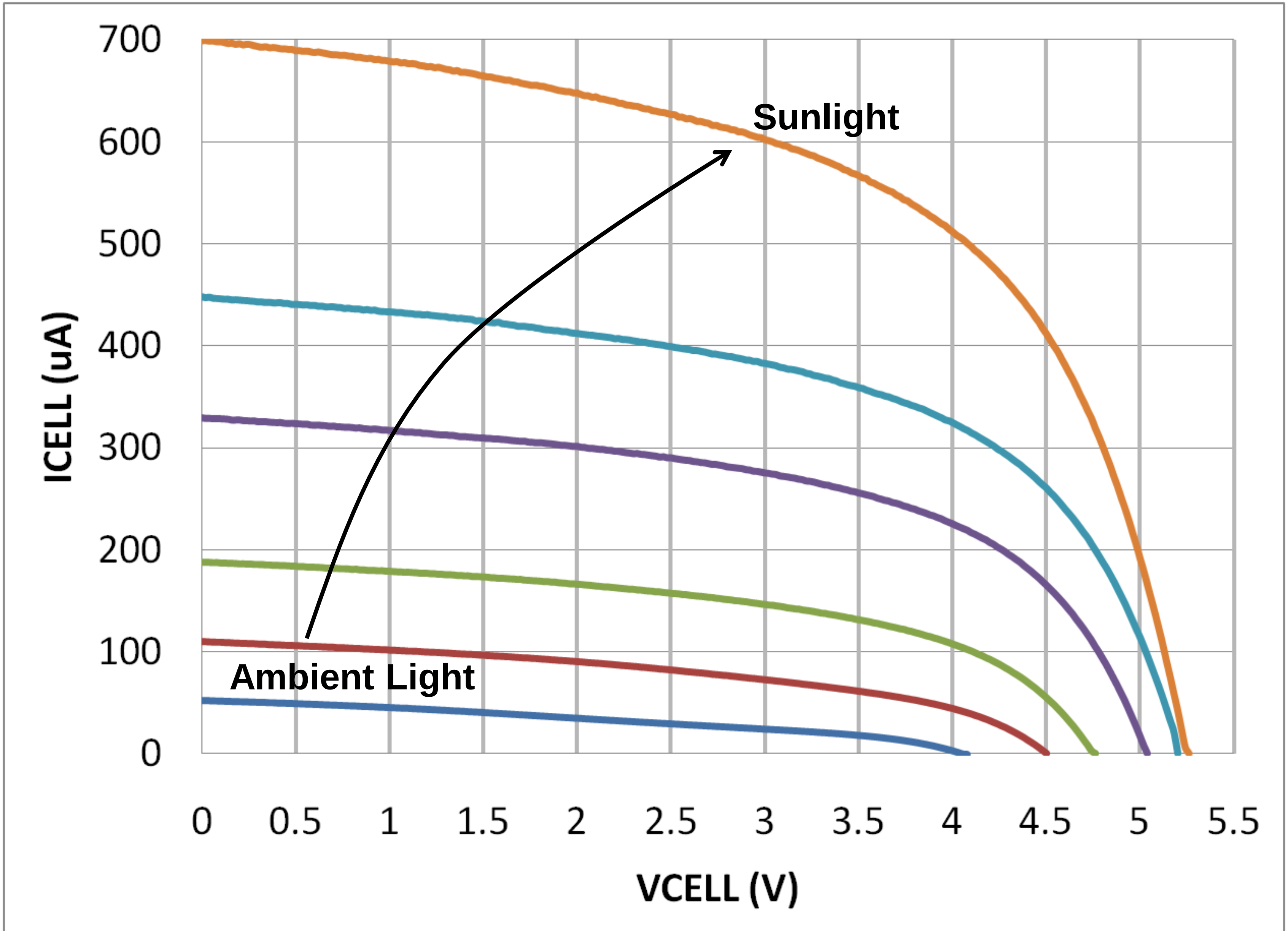


*US Department of Energy

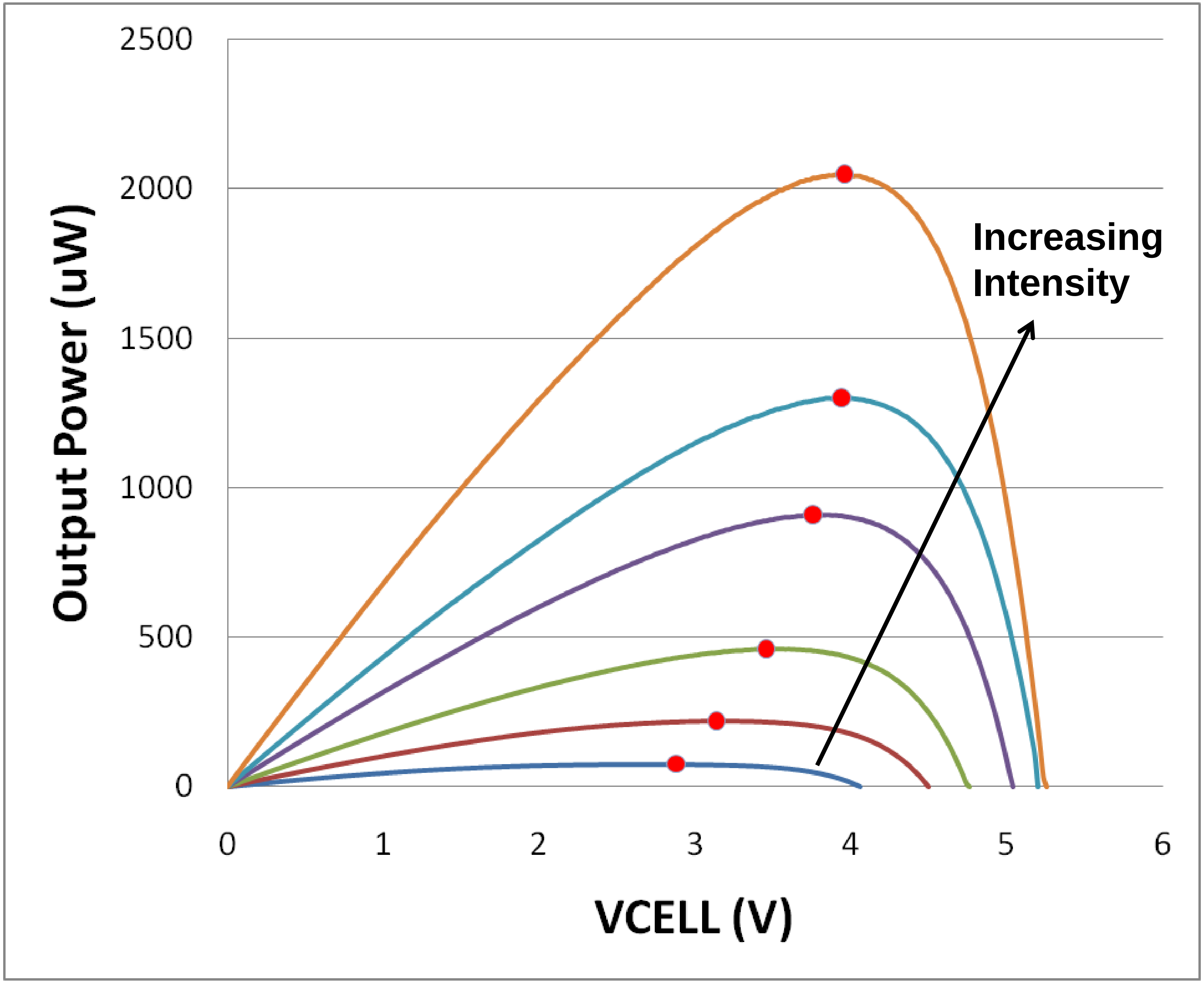


- Incident light generates electron-hole pairs
- I_{SC} proportional to light intensity
- Solar cell can be modeled as current source into a diode

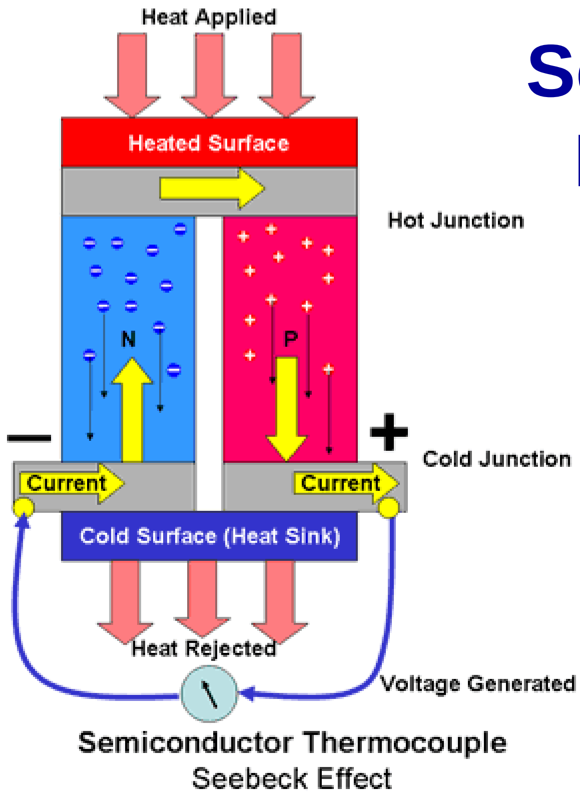
I-V curves with light intensity



Output power curves with light intensity

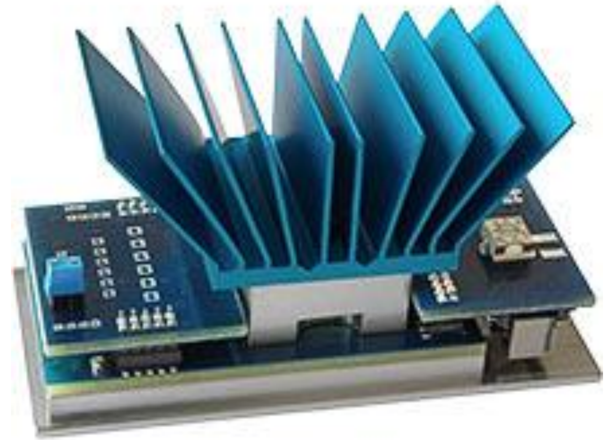


Thermoelectric Energy Harvesters



Seebeck Effect

[Micropelt]

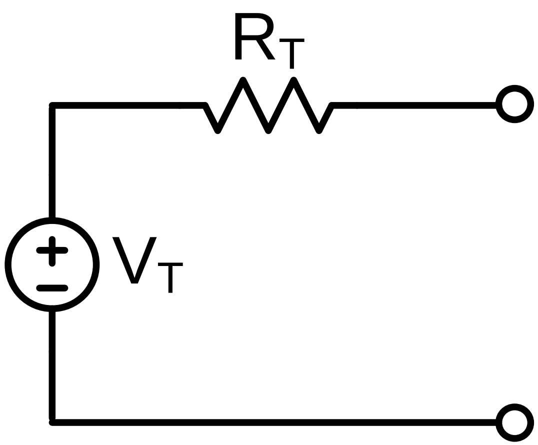


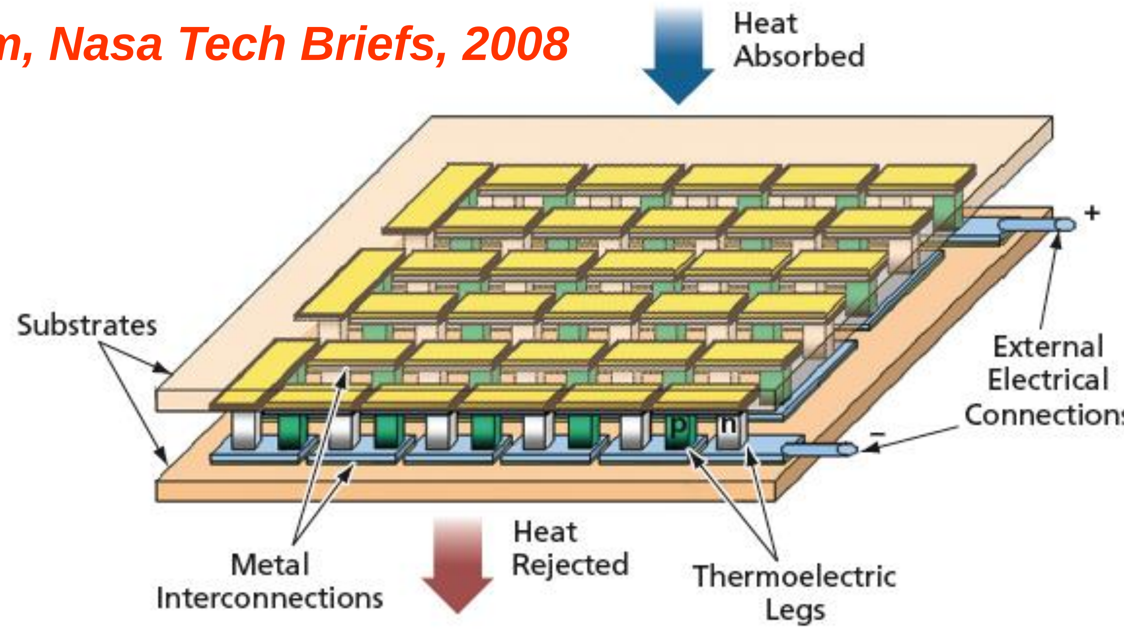
- Convert heat energy to electrical energy
- Bismuth Telluride preferred due to superior thermal properties
- One p-n leg generates ~ 0.2mV/K

Equivalent Circuit of Thermal Harvester

$$\boxed{V_T = S\Delta T}$$

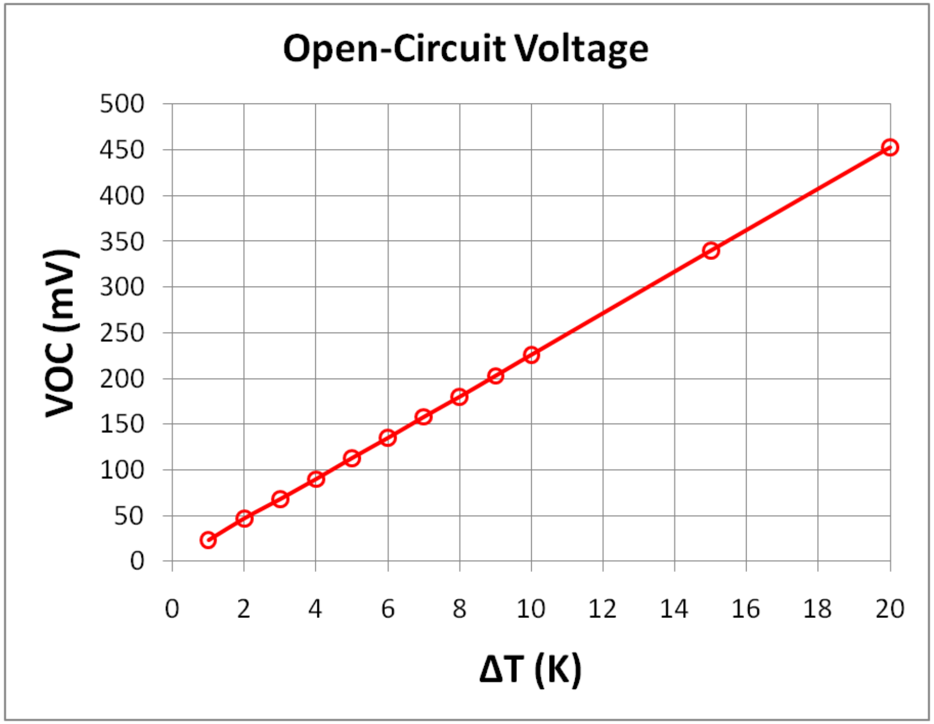
Lim, Nasa Tech Briefs, 2008

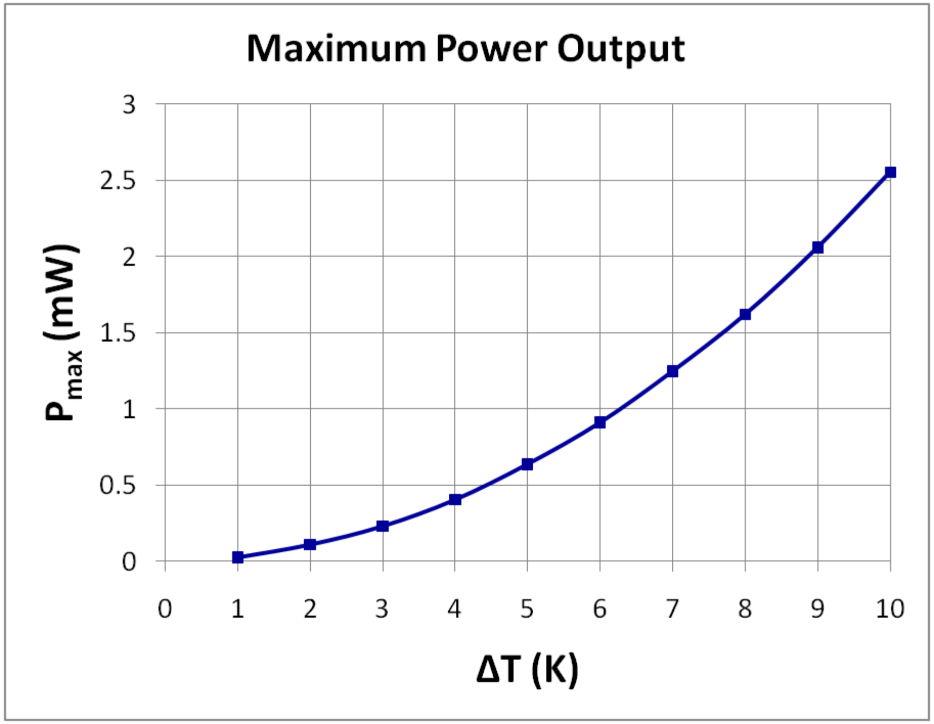




- Electrically in series, Thermally in parallel
- Open-circuit voltage proportional to temperature difference across TEG

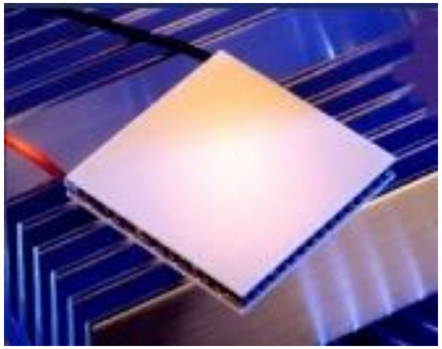
TEG Characteristics



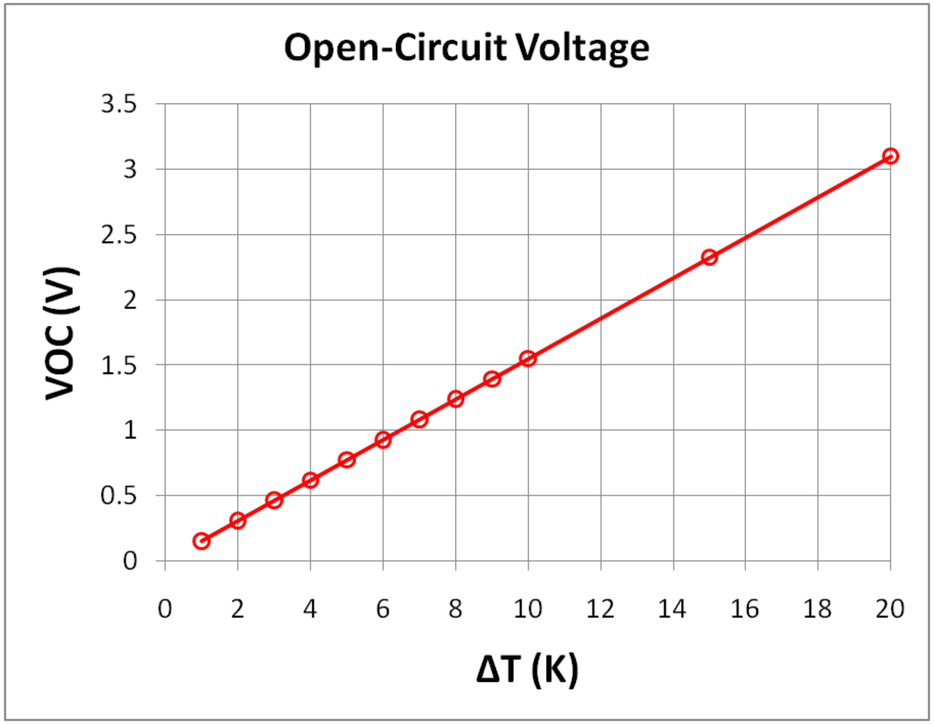


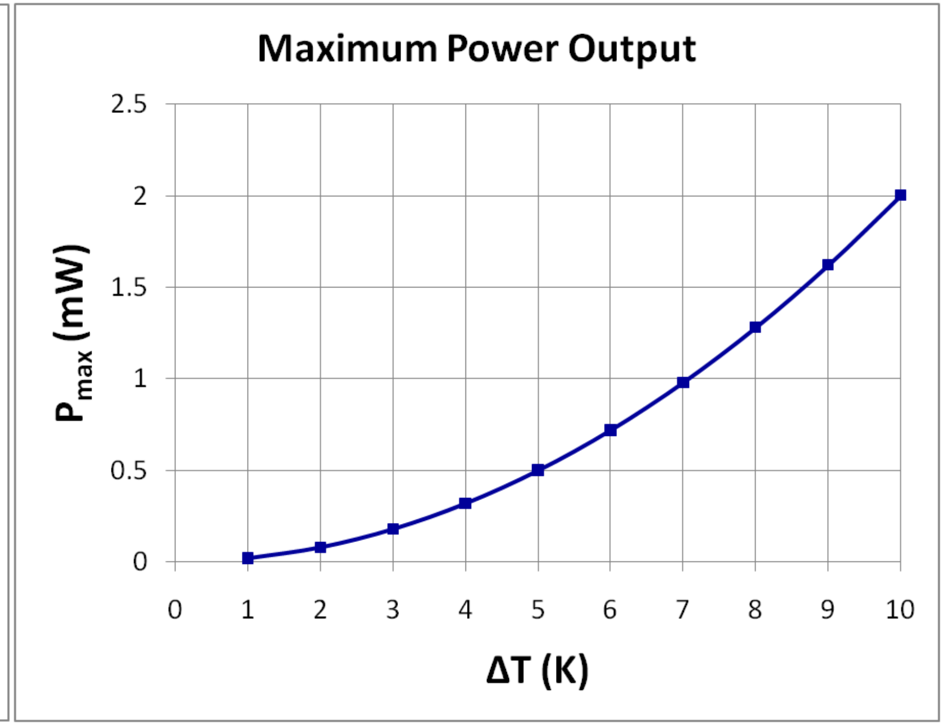
[Tellurex]

- Tellurex G1-1.0-127-1.27
- $S = 23mV/K$; $R_T = 5\Omega$
- http://www.tellurex.com/power modules/p127.html

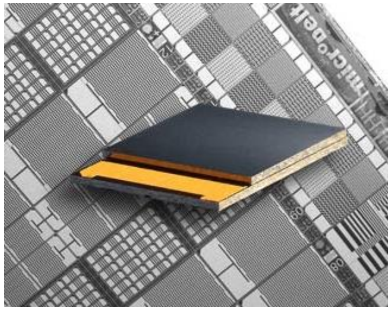


TEG Characteristics





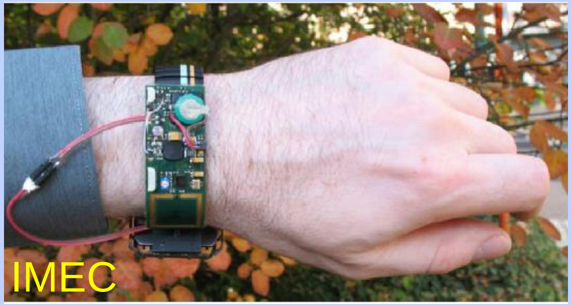
[Micropelt]



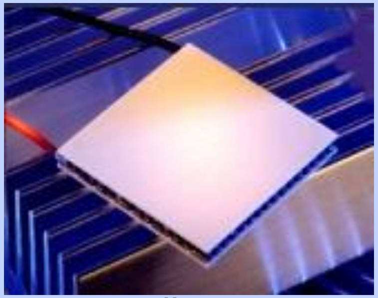
- Micropelt MPG-D751
- S = 155mV/K; R_T = 300Ω
- http://micropelt.com/products/thermogenerator.php

Body Heat Powered Electronics

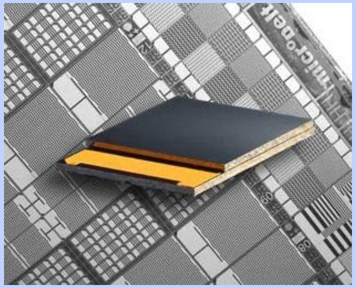
System Concept



Thermo-Electric Devices

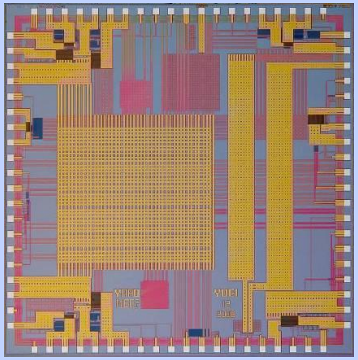


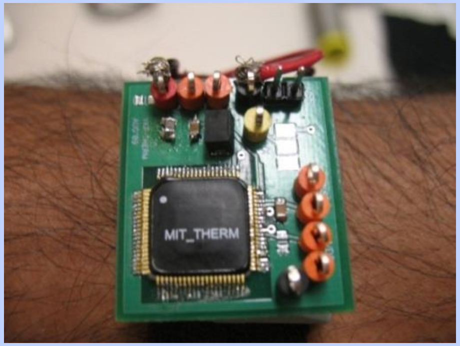
Tellurex



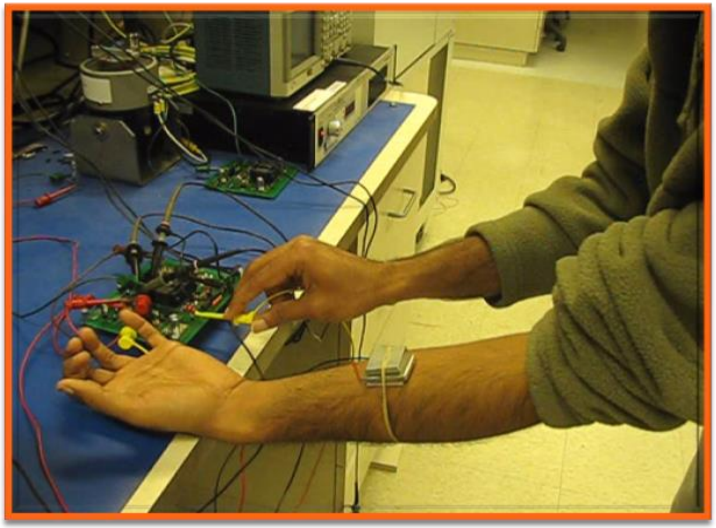
Micro-pelt

Thermal Energy Chip



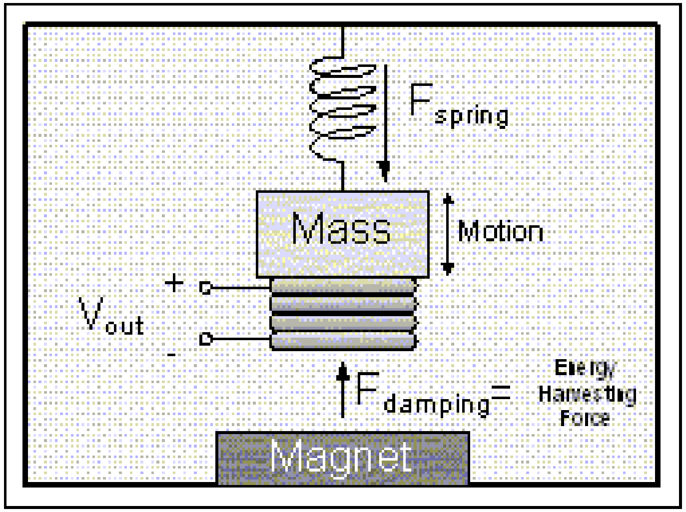


[Y. Ramadass and A. Chandrakasan, ISSCC 2010]



For low-power wearable electronics

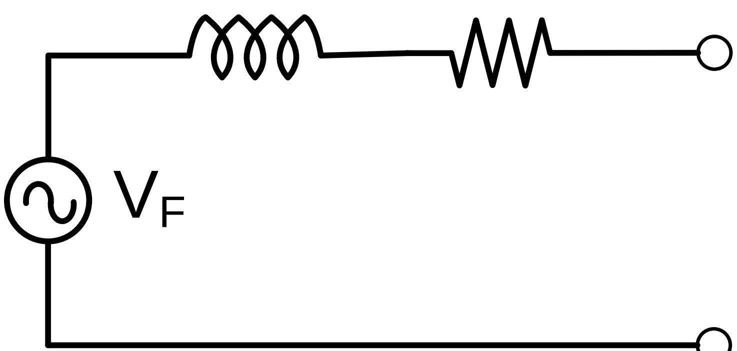
Electromagnetic Vibration Harvesters

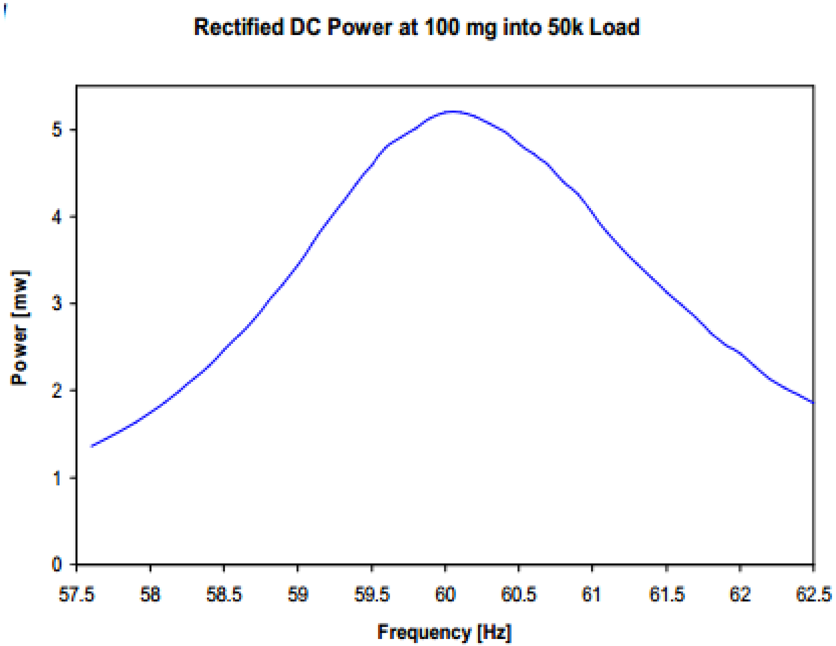


[Perpetuum]

[FerroSolutions]

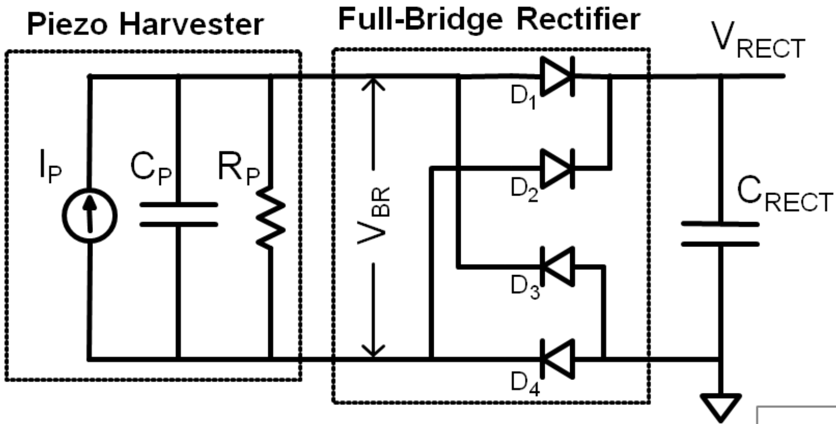
Simple equivalent circuit at resonance





FerroSolutions VEH-460

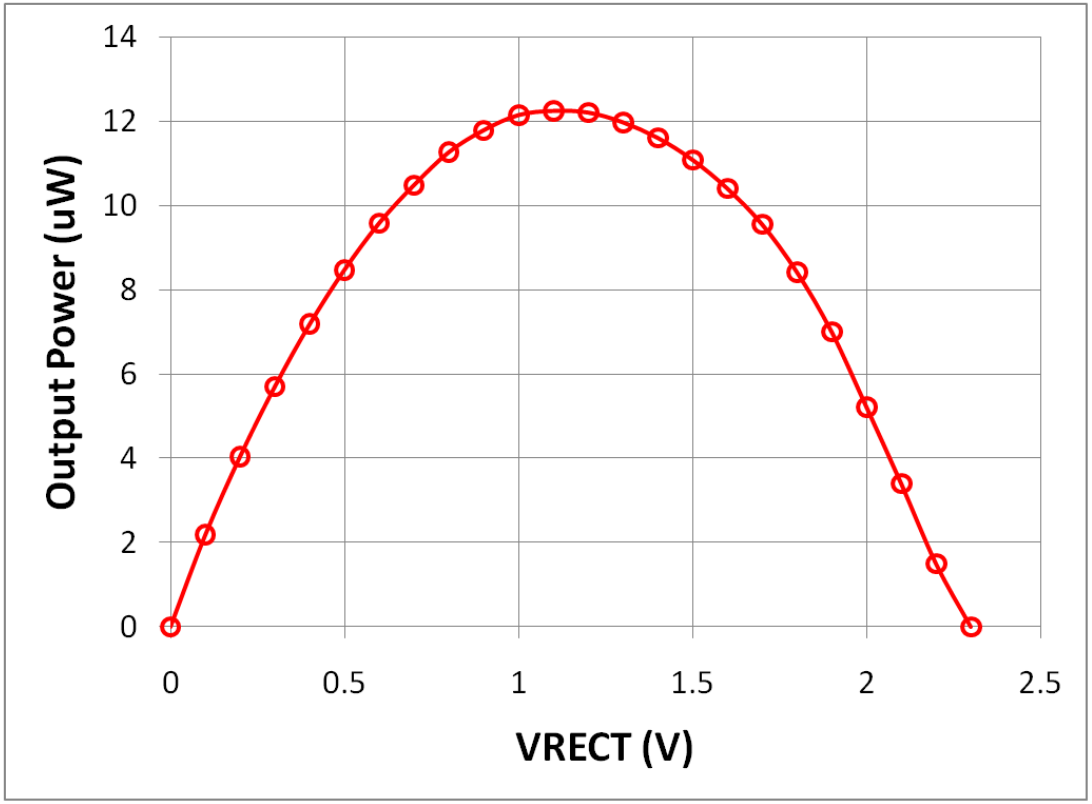
Piezoelectric Vibration Harvesters



Mide Volture v22b

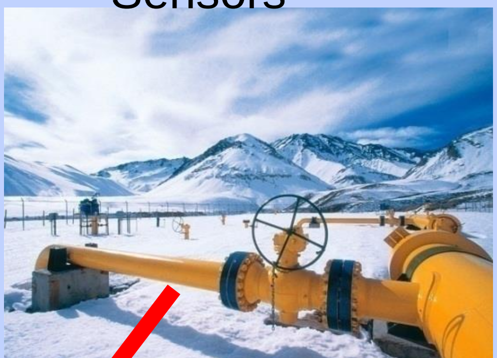
- V_P = 2.3V
- C_P = 12nF
- *f* = 225Hz

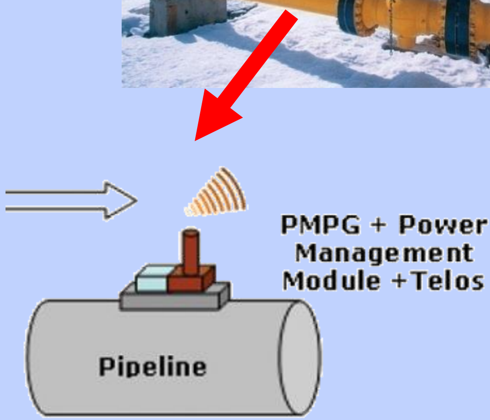
Y. Ramadass, ISSCC, 2009



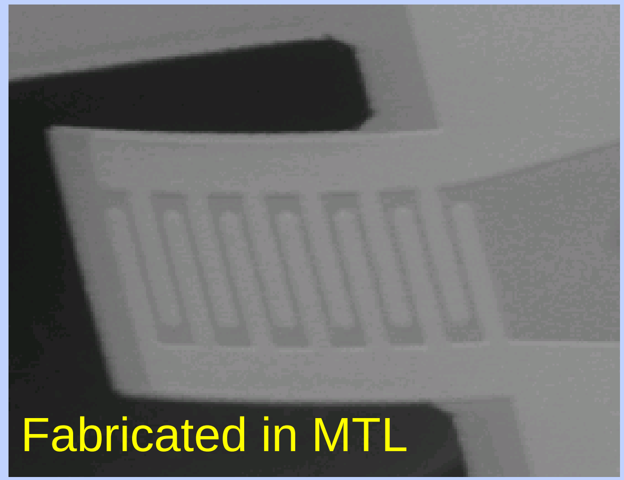
Vibration-to-Electric Energy

Self-powered Wireless Corrosion Monitoring Sensors

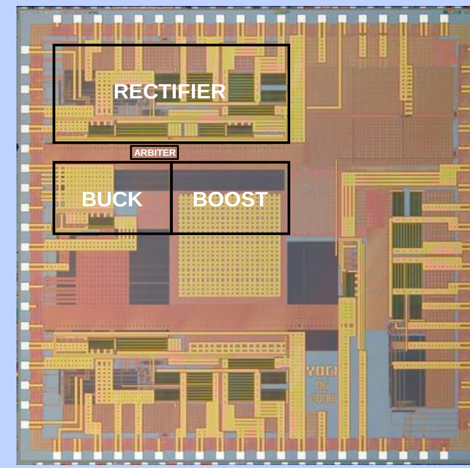




Piezoelectric Micro-Power Generators



Power Converter



Sang-Gook Kim (MIT)

10μW -100μW generated

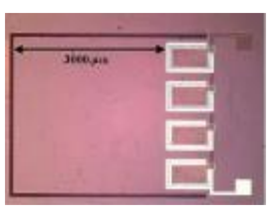
Vibrations Power Distributed Sensor Devices
(Battery-less Operation)

Energy Harvesting Sources

Energy Source	Characteristics	Efficiency	Harvested Power
Light	Outdoor Indoor	10~24%	10 mW/cm^2 10 µW/cm^2
Thermal	Human Industrial	~0.1% ~3%	60 µW/cm^2 ~1-10 mW/cm^2
Wireless	Near field Far field	> 60% < 1%	1-10 mW/cm^2 <10 µW/cm^2
Vibration	~Hz–human ~kHz–machines	25~50%	~4 µW/cm^3 ~800 µW/cm^3

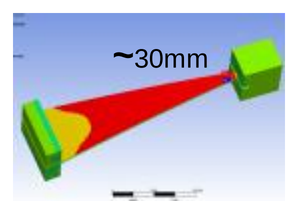
Seiko watch
~5uW

Holst Center
~40uW



2 channel EEG
~1mW

AdaptivEnergy
~10mW

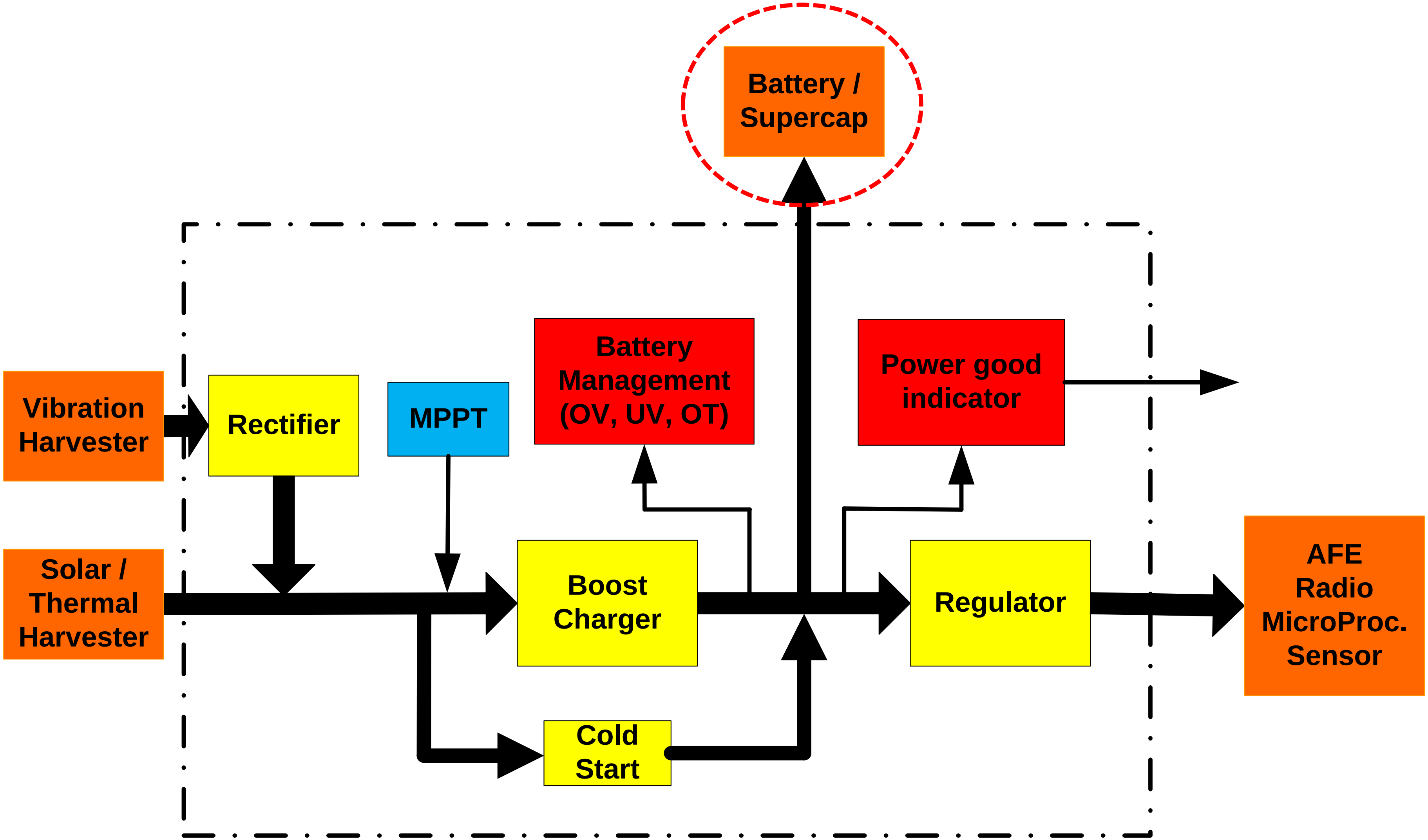


Elastometer
~800mW

BigBelly
~40W

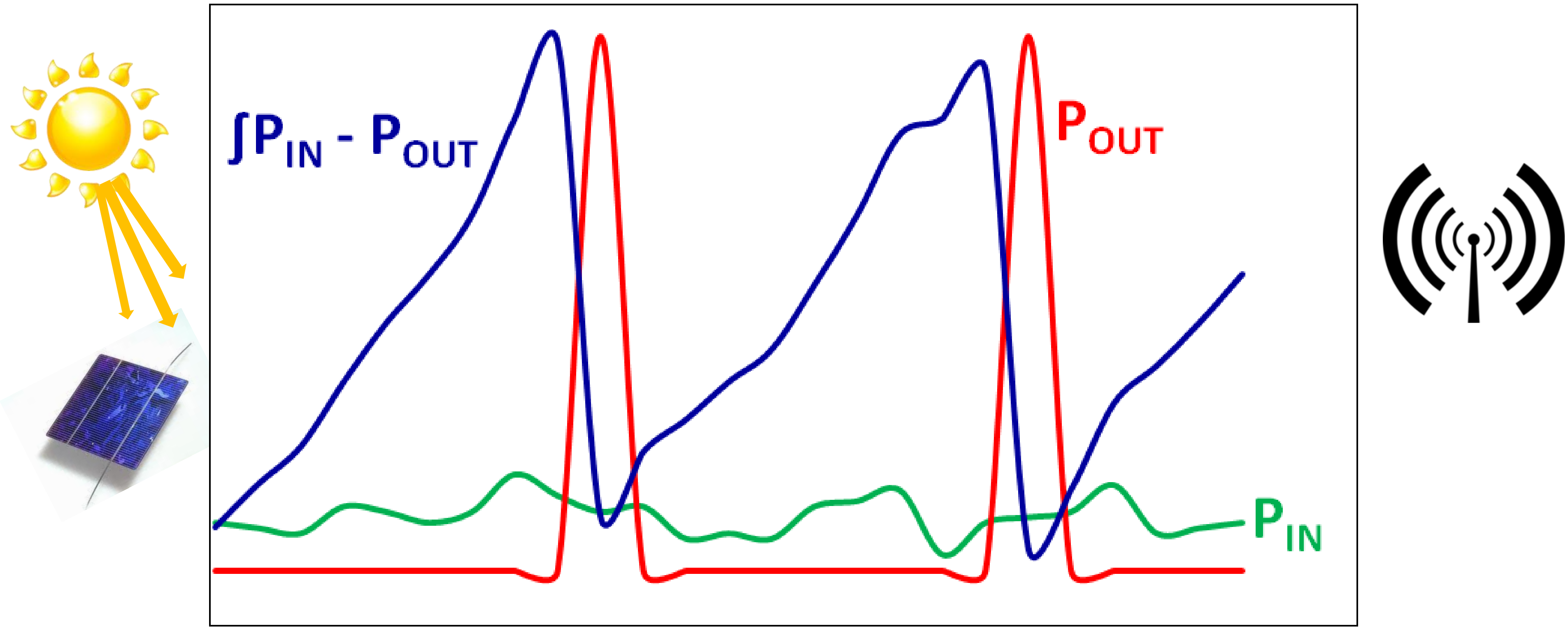
1uW 10uW 100uW 1mW 10mW 100mW 1W+

Energy Storage Options



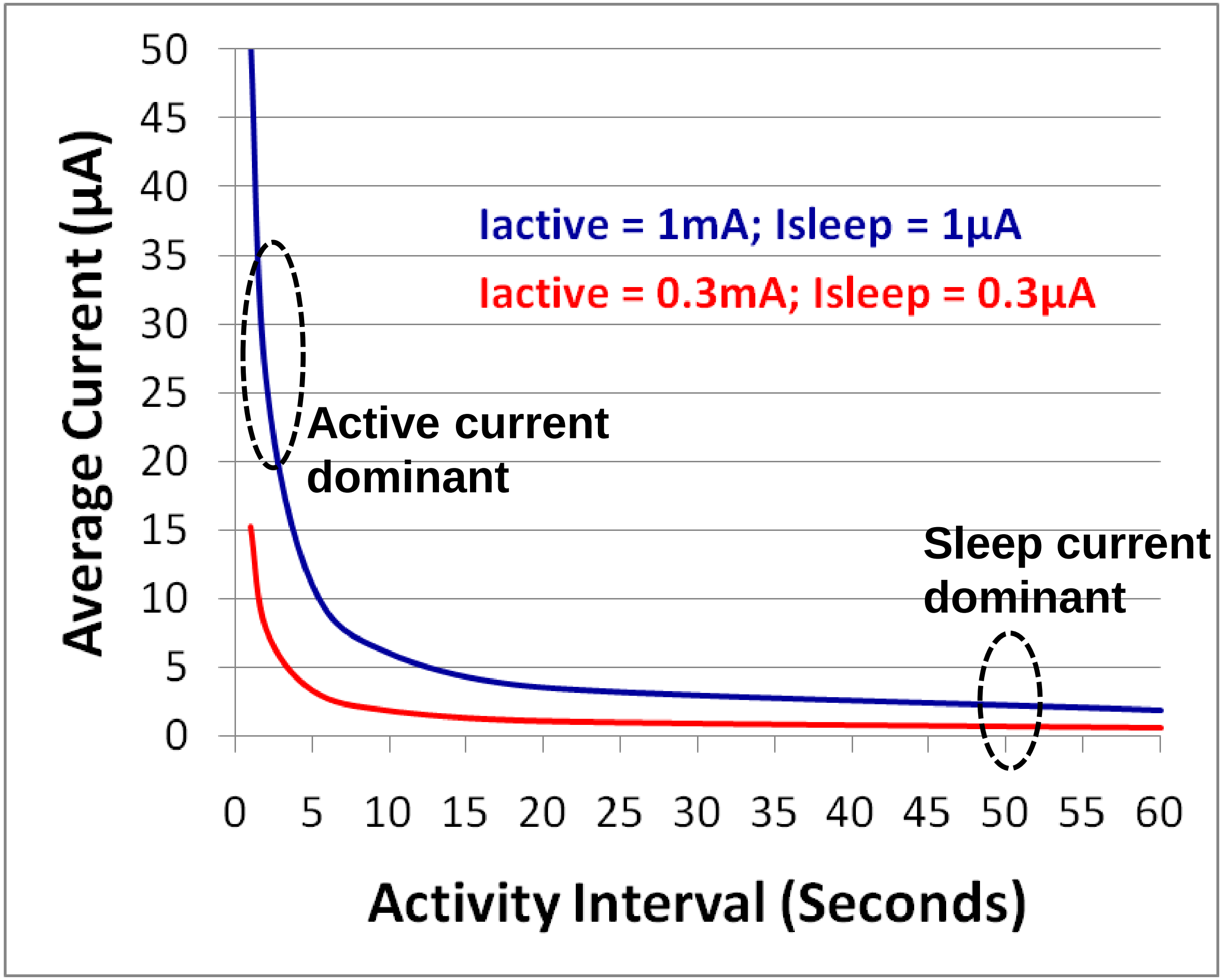
Store extracted energy from harvesters and provide to load

Energy Buffer



- Accumulate input power
- Provide peak output power
- Smooth out input, output power imbalances

Duty Cycle Impact on Current



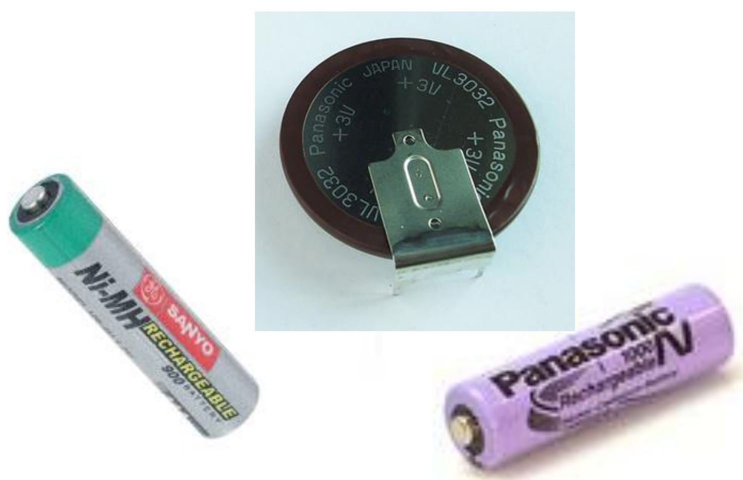
Pulse Width = 50ms

$$D = \frac{Pulse\,Width}{Activity\ Interval}$$

$$\boxed{I(avg) = Iactive * D + Isleep * (1 - D)}$$

Energy Storage Options

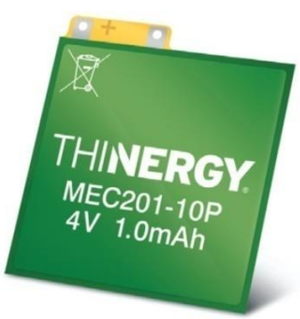
	Conventional Batteries
Recharge Cycles	100s
Self Discharge	Moderate
Charge Time	Hours
Impedance	Low - High
Physical Size	Large
Capacity	0.3-2500mAH



- NiCd, NiMH, Li chemistries
- AA, AAA batteries have high capacity, low internal impedance, higher self discharge
- Li coin cells have low capacity, high internal impedance, smaller form factor

Energy Storage Options

	Conventional Batteries	Thin Film Batteries
Recharge Cycles	100s	5k-10k
Self Discharge	Moderate	Negligible
Charge Time	Hours	Minutes
Impedance	Low - High	High
Physical Size	Large	Small
Capacity	0.3-2500mAH	12-2200µAH



- Solid-state LiPON electrolyte
- Higher output currents compared to coin cells
- Extremely low self-discharge
- Variety of form factors, intrinsically safe, high temp.

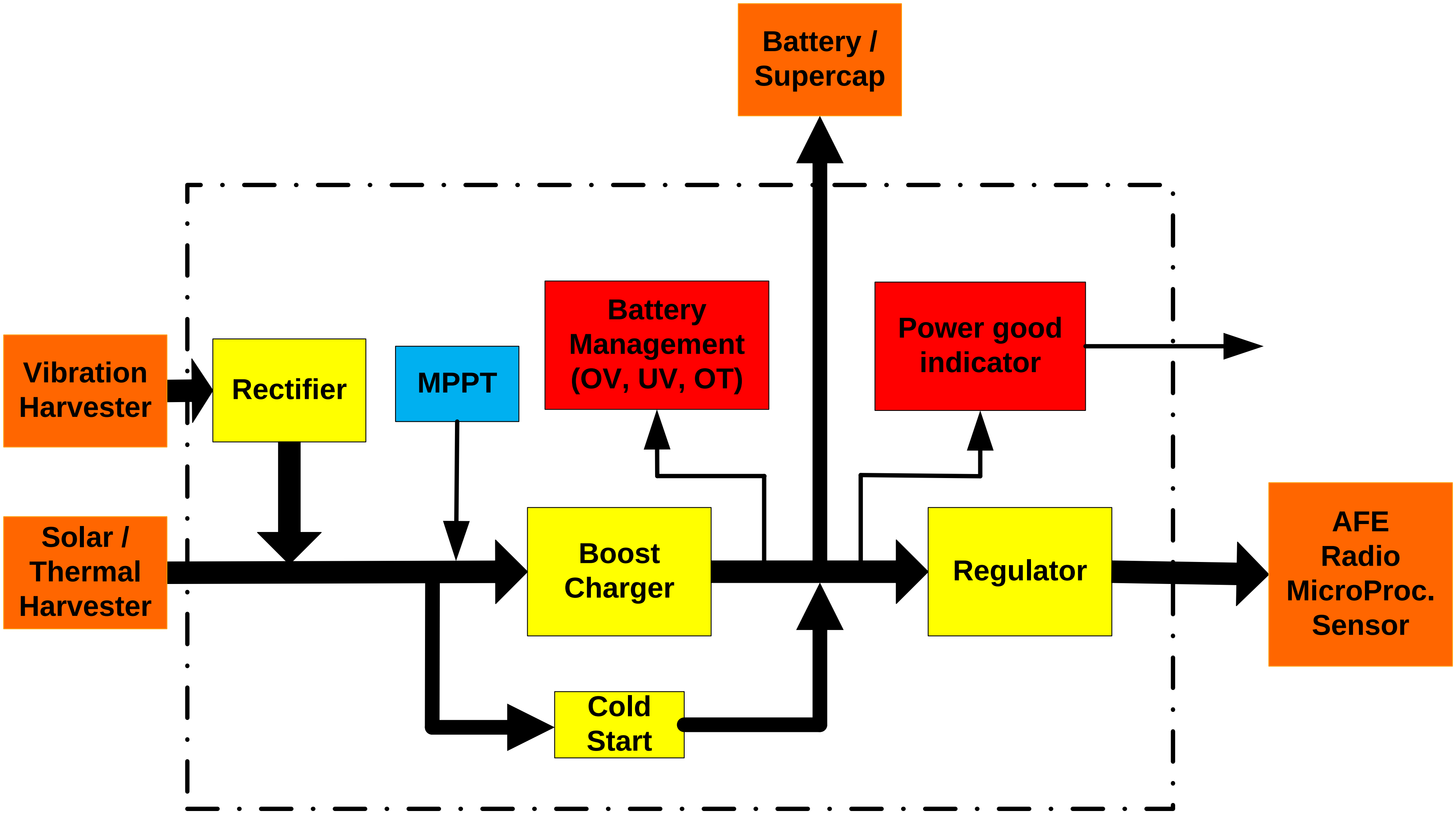
Energy Storage Options

	Conventional Batteries	Thin Film Batteries	Supercaps
Recharge Cycles	100s	5k-10k	Millions
Self Discharge	Moderate	Negligible	High
Charge Time	Hours	Minutes	Sec-Minutes
Impedance	Low - High	High	Low
Physical Size	Large	Small	Medium
Capacity	0.3-2500mAH	12-2200µAH	10-100µAH

[AVX]

- Supports high peak output currents
- Very high leakage currents
- Wide range of operating temperature

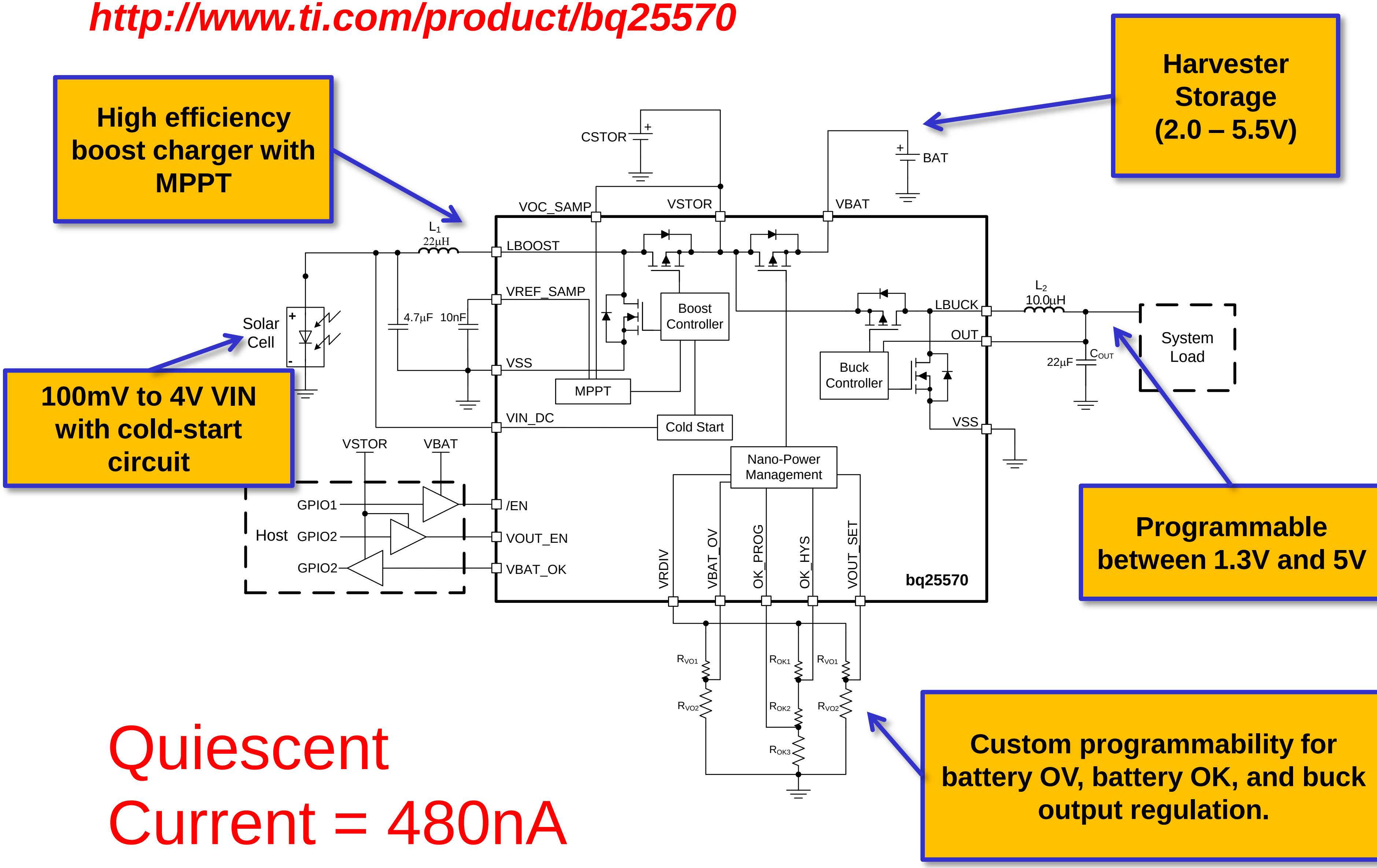
Energy Processor



Take input energy from harvester and charge the storage element efficiently

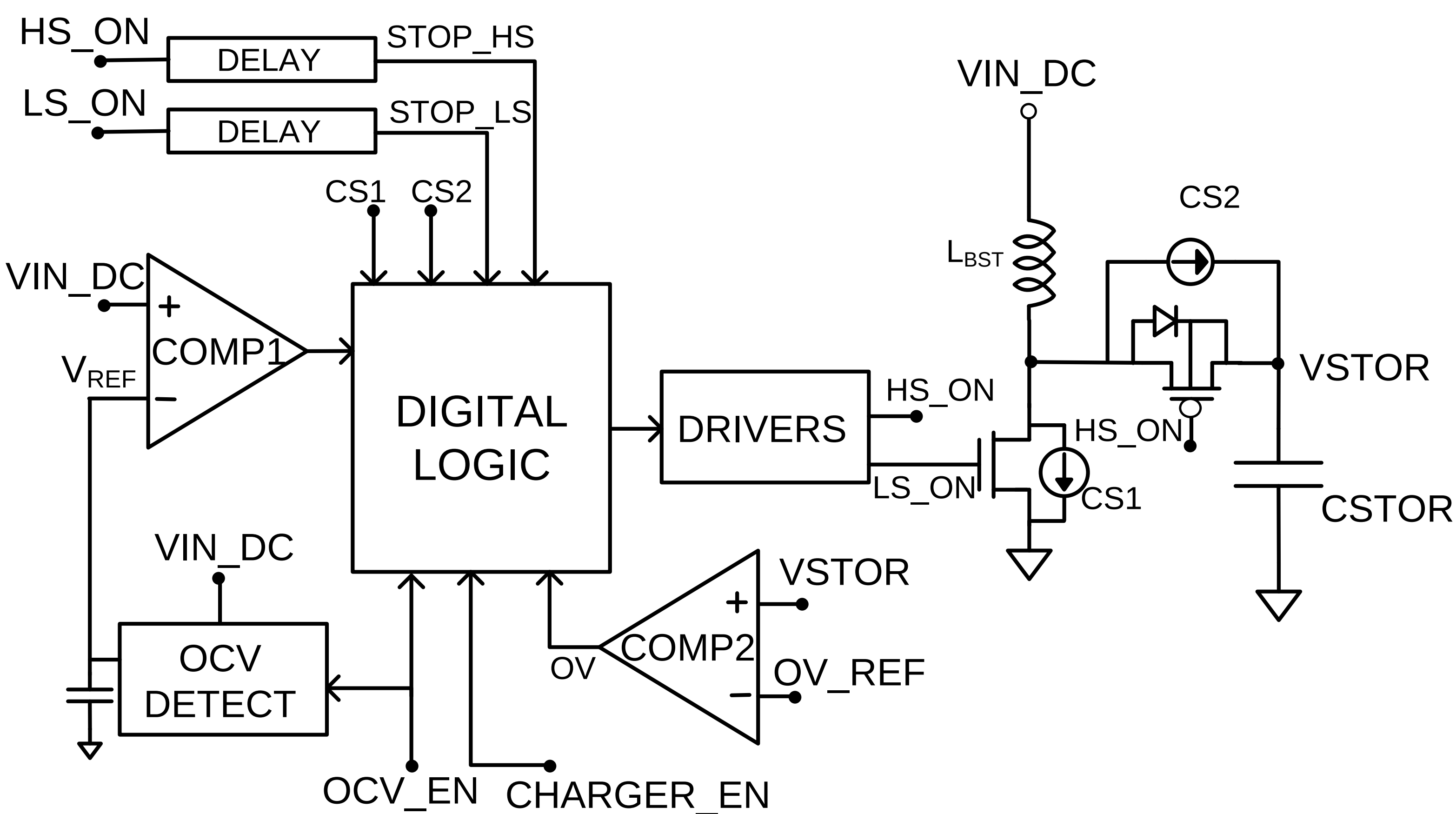
Energy Mgmt. IC -BQ25570

http://www.ti.com/product/bq25570



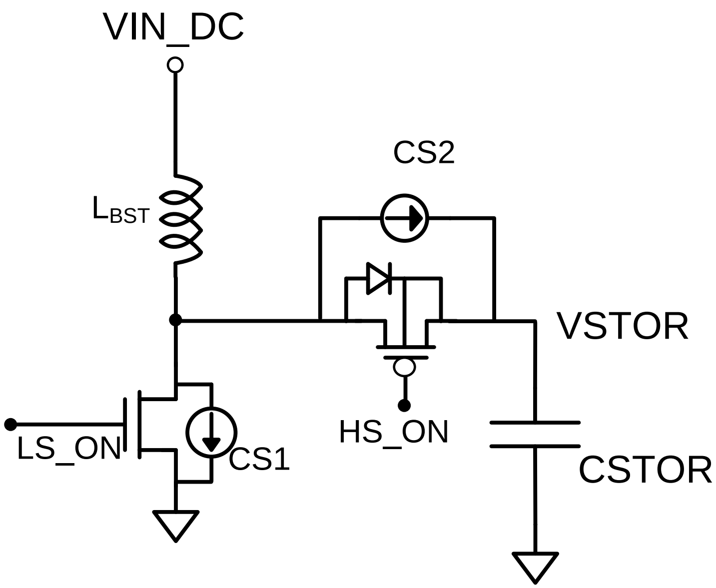
Quiescent Current = 480nA

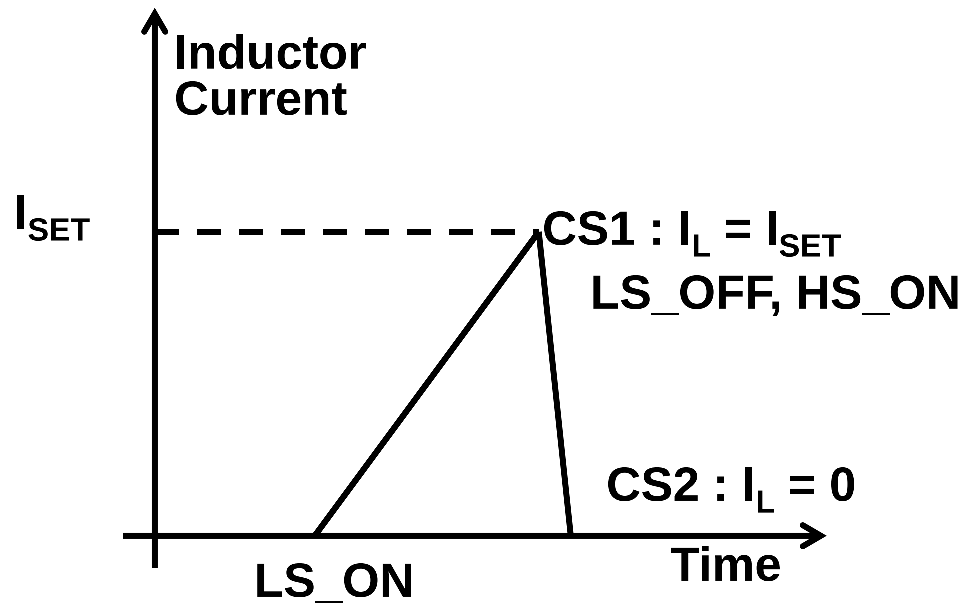
BQ25570 Charger Architecture



- Synchronous boost converter with input regulation
- 80mV – 4V input voltage
- 10µA – 100mA input current

Charger Operation



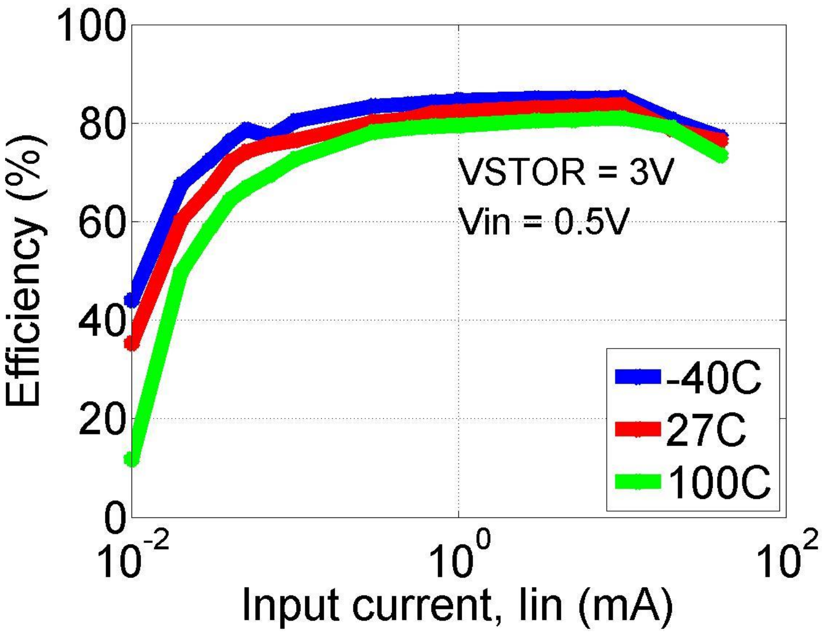


- When VIN_DC > V_{REF}
  - LS_ON = hi and LS_ON remains high till I_L hits I_{SET}
- Once CS1 goes high (i.e $I_L = I_{SET}$),
  - LS_ON =lo and HS_ON = hi
- HS_ON remains high till I_L = 0 (CS2 detects this)

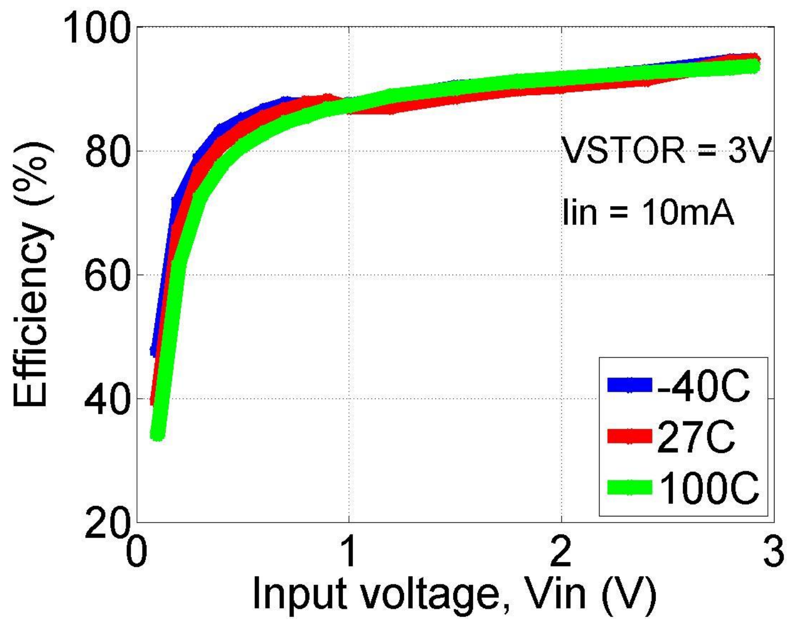
BQ25570 Charger Efficiency

- **Single** cell solar operation in indoor light (200 lux)
- Harvesting from thermoelectric generators

Eff Vs Iin



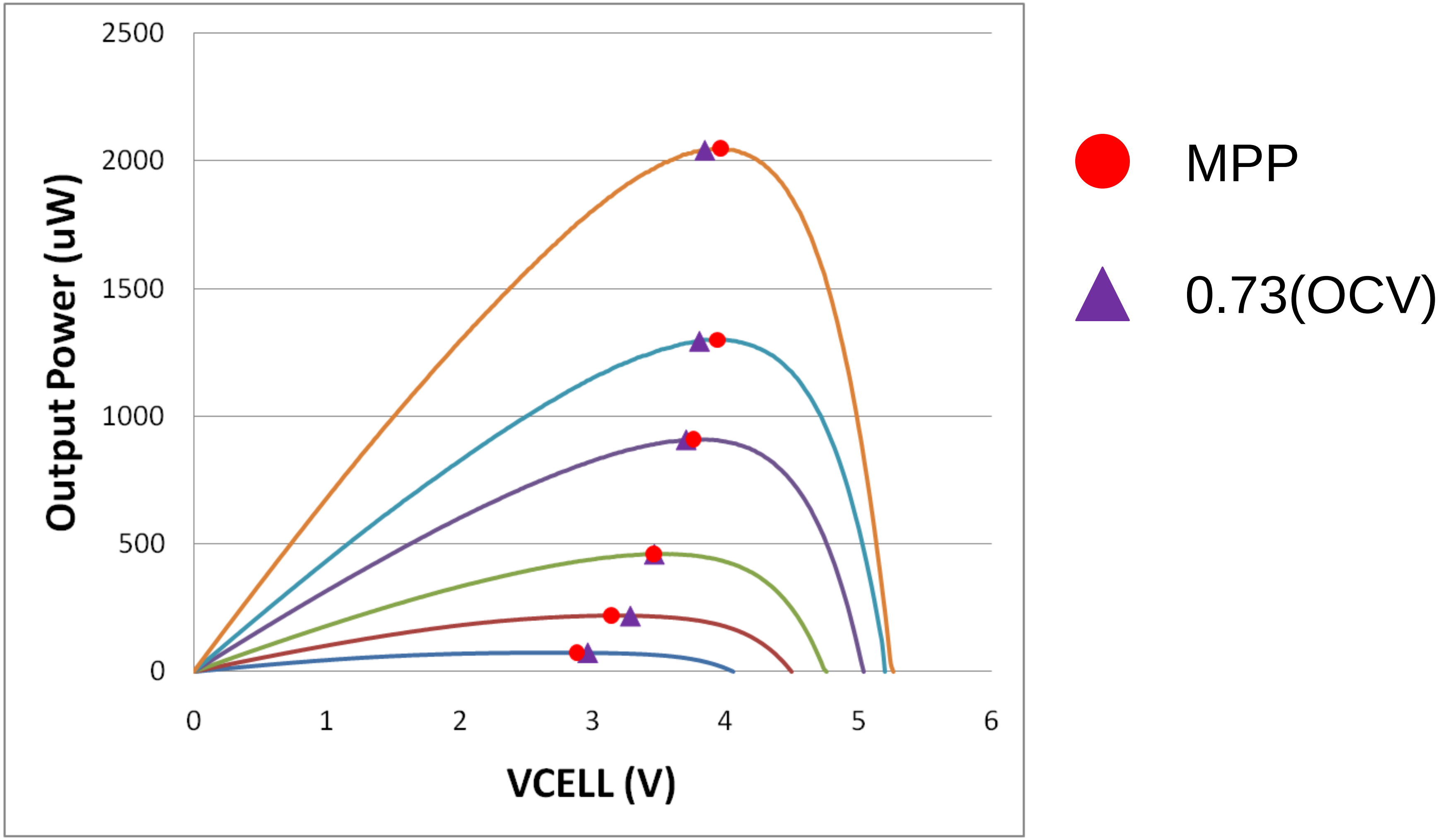
Eff Vs Vin



- 35% efficiency with 10µA input at 0.5V
- > 80% above 100µA.

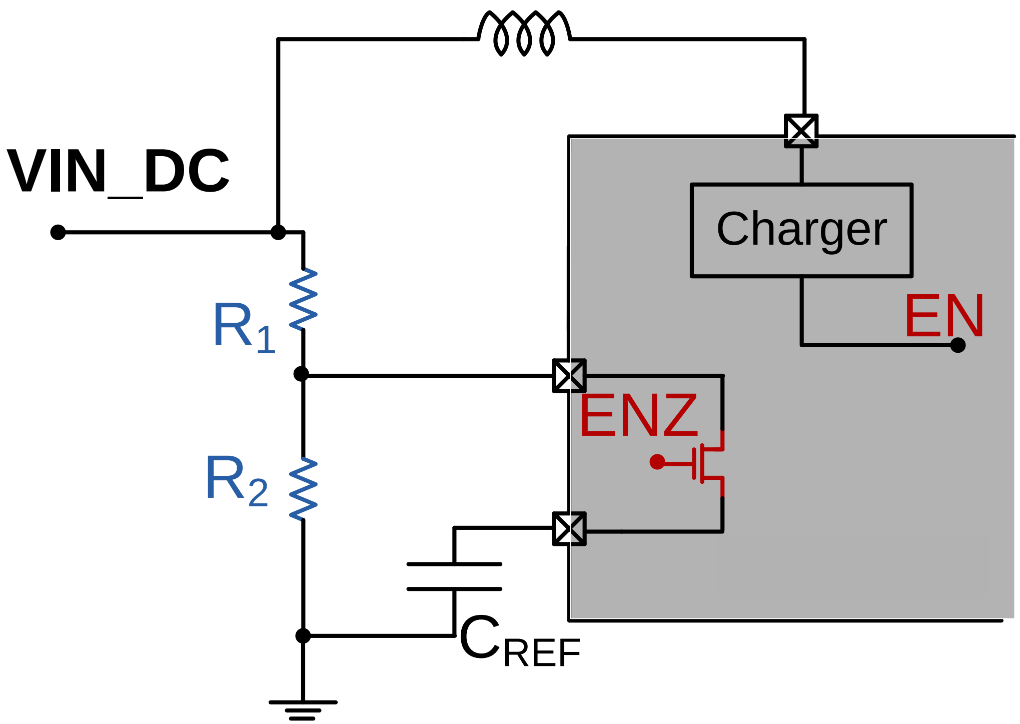
- 38% efficiency with 100mV input at 10mA
- >80% above 0.5V

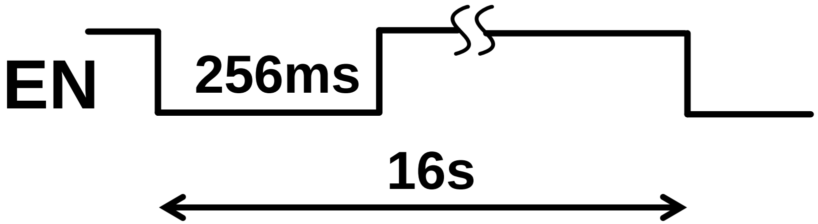
Revisiting solar MPP curves



Output power levels within 0.5%

BQ25570 Maximum Power Point Tracking

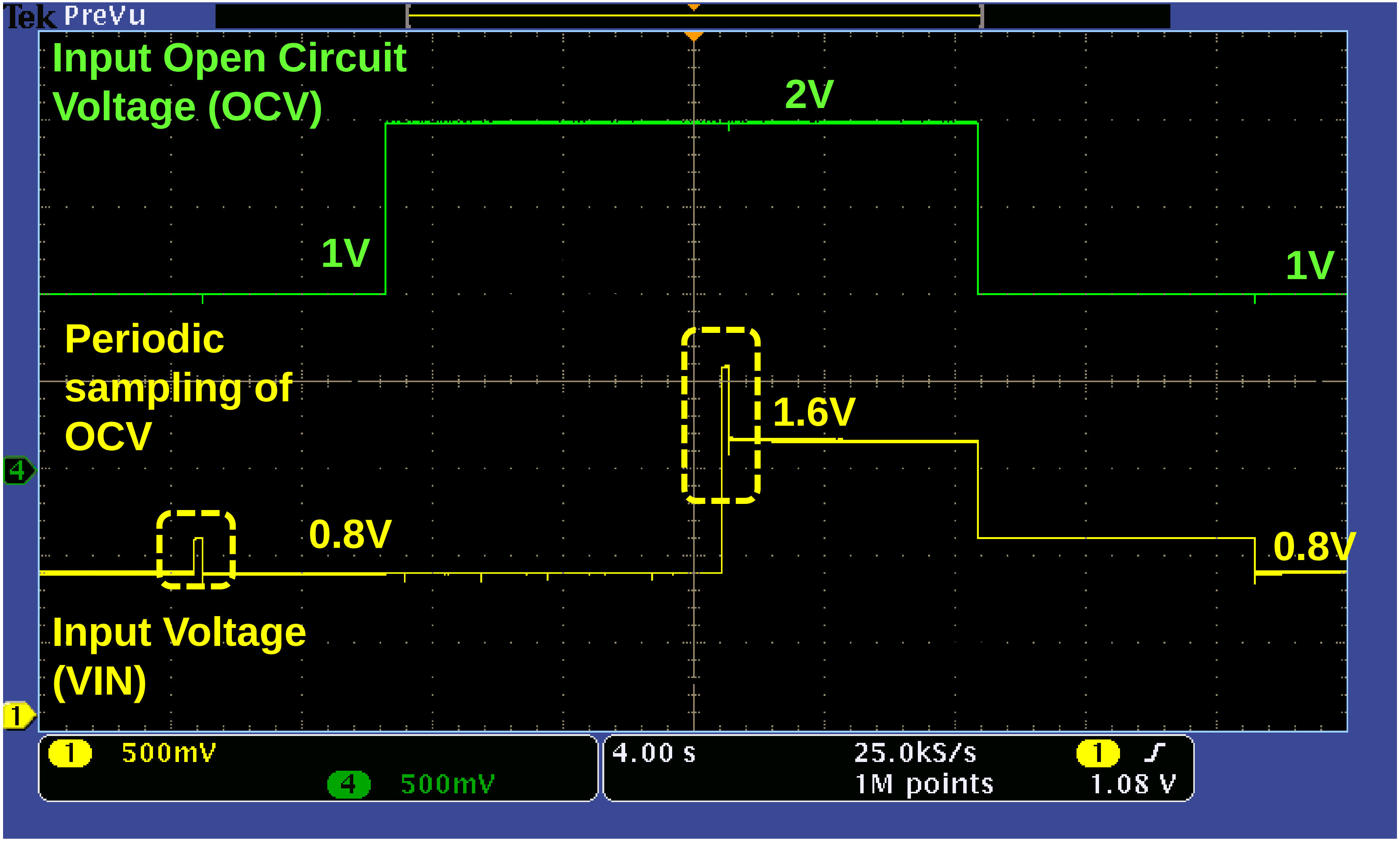




	Solar	TEG
MPPT fraction	~75%	50%

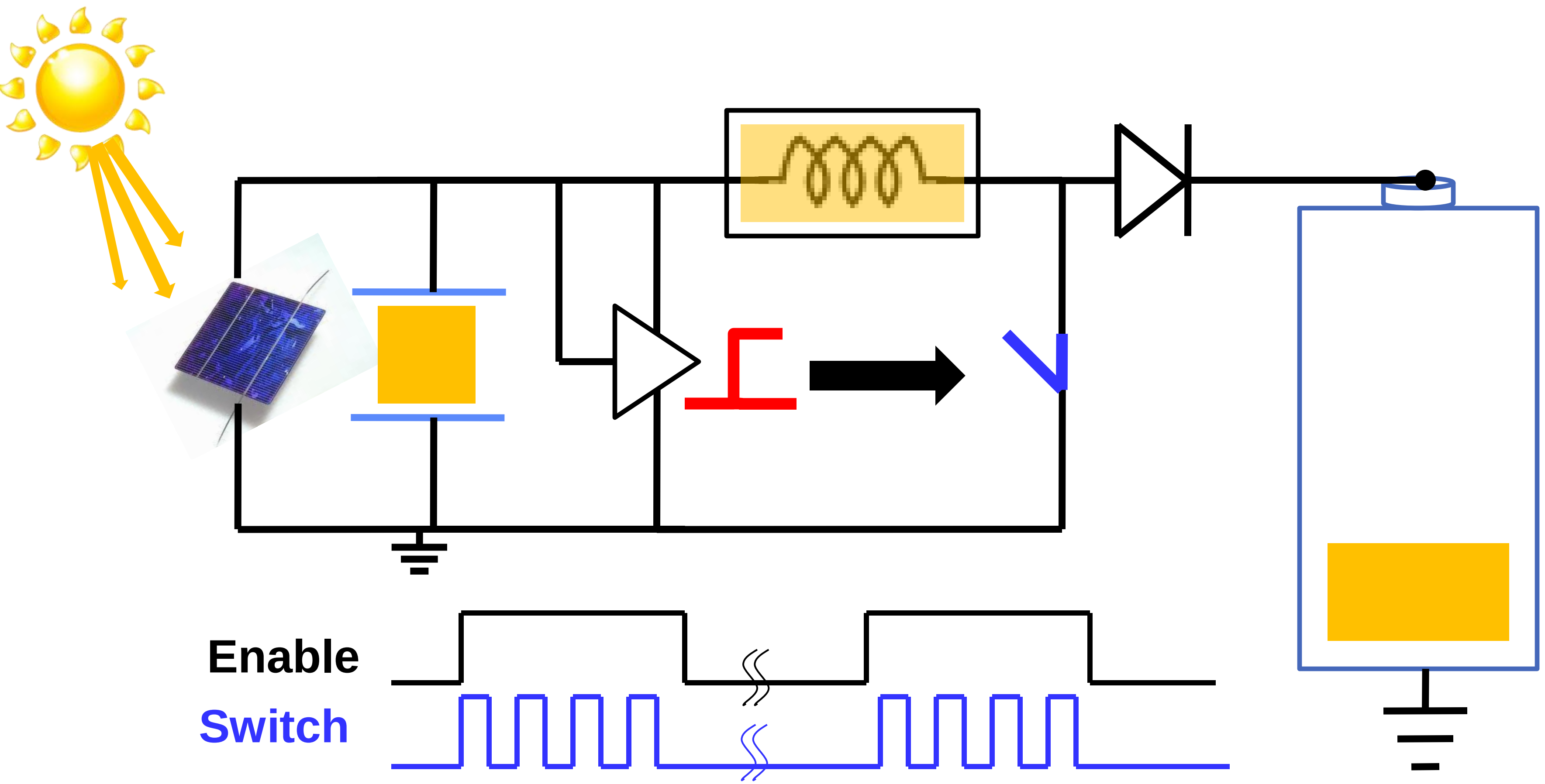
- Open circuit voltage based MPPT
- Charger periodically turned off using **EN** signal
- IC samples and holds fraction of OCV on external capacitor
- Charger regulates input to value held on capacitor

MPPT waveforms

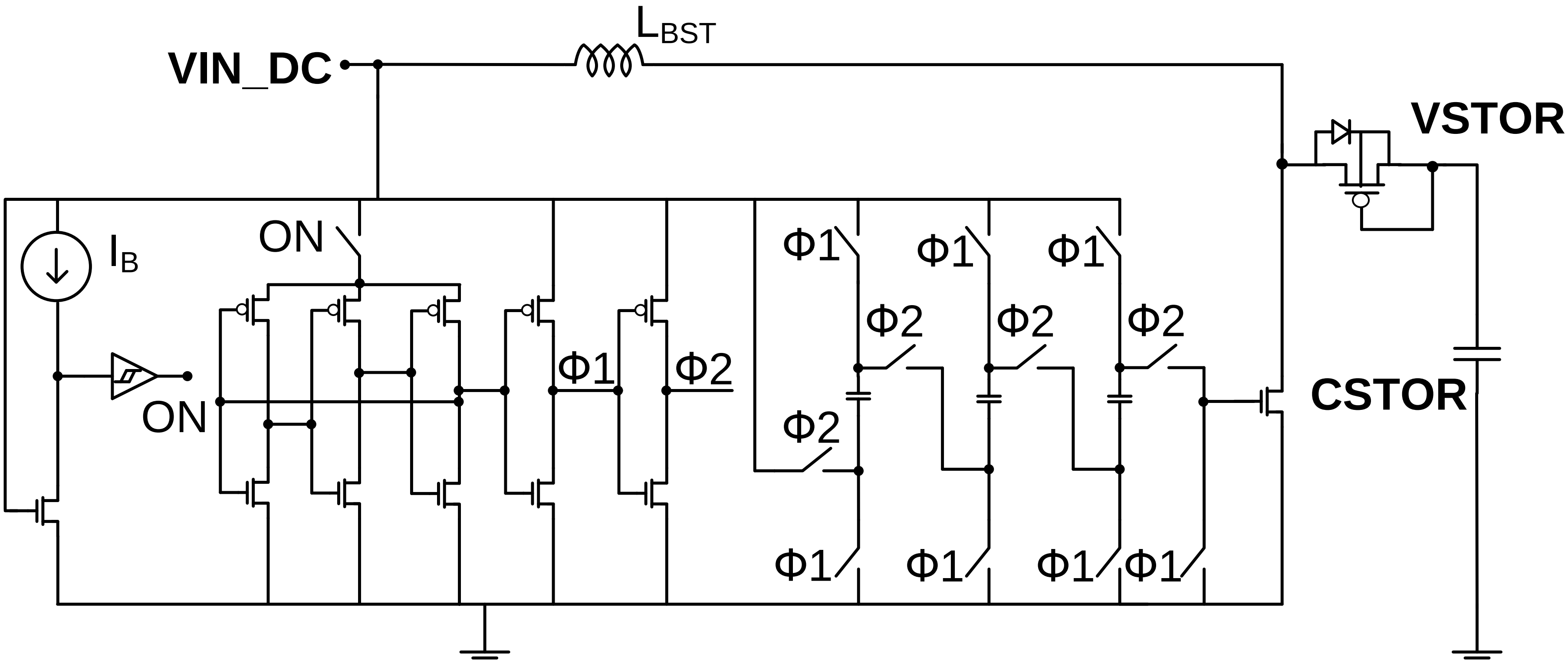


Cold Start

- Function : Start system with depleted storage
- Architecture : **Input** powered boost converter



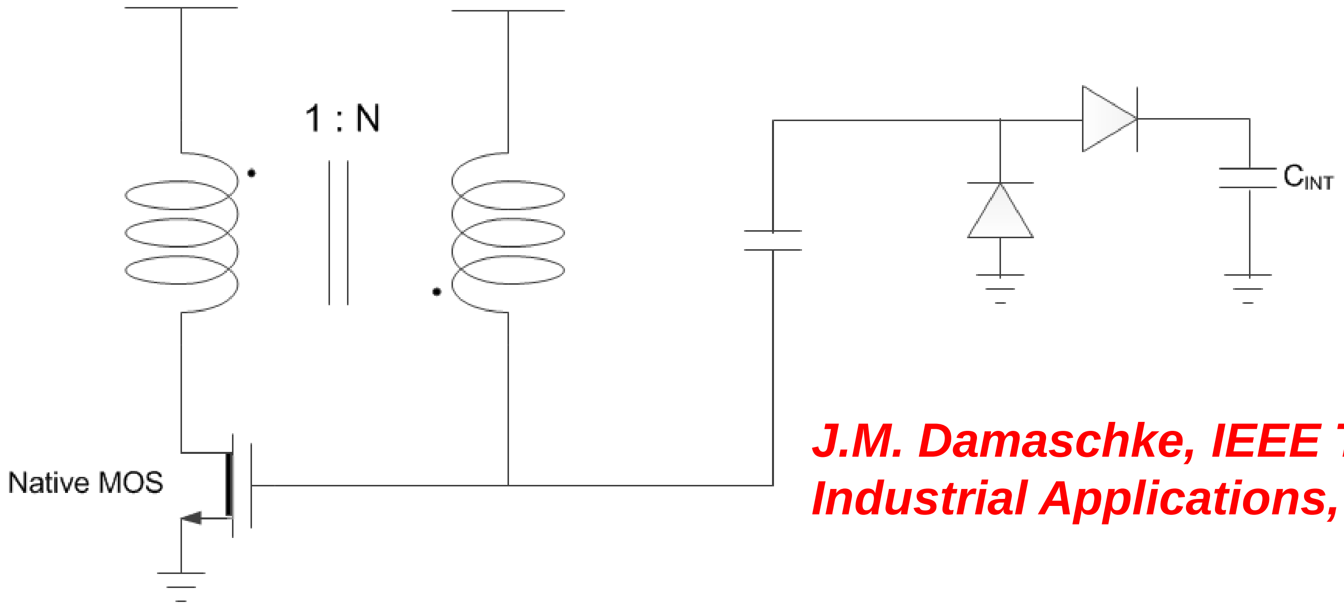
330mV Cold Start Circuit



K. Kadirvel, ISSCC, 2012

- Low V_t low side switch
- Body diode of main charger high side switch

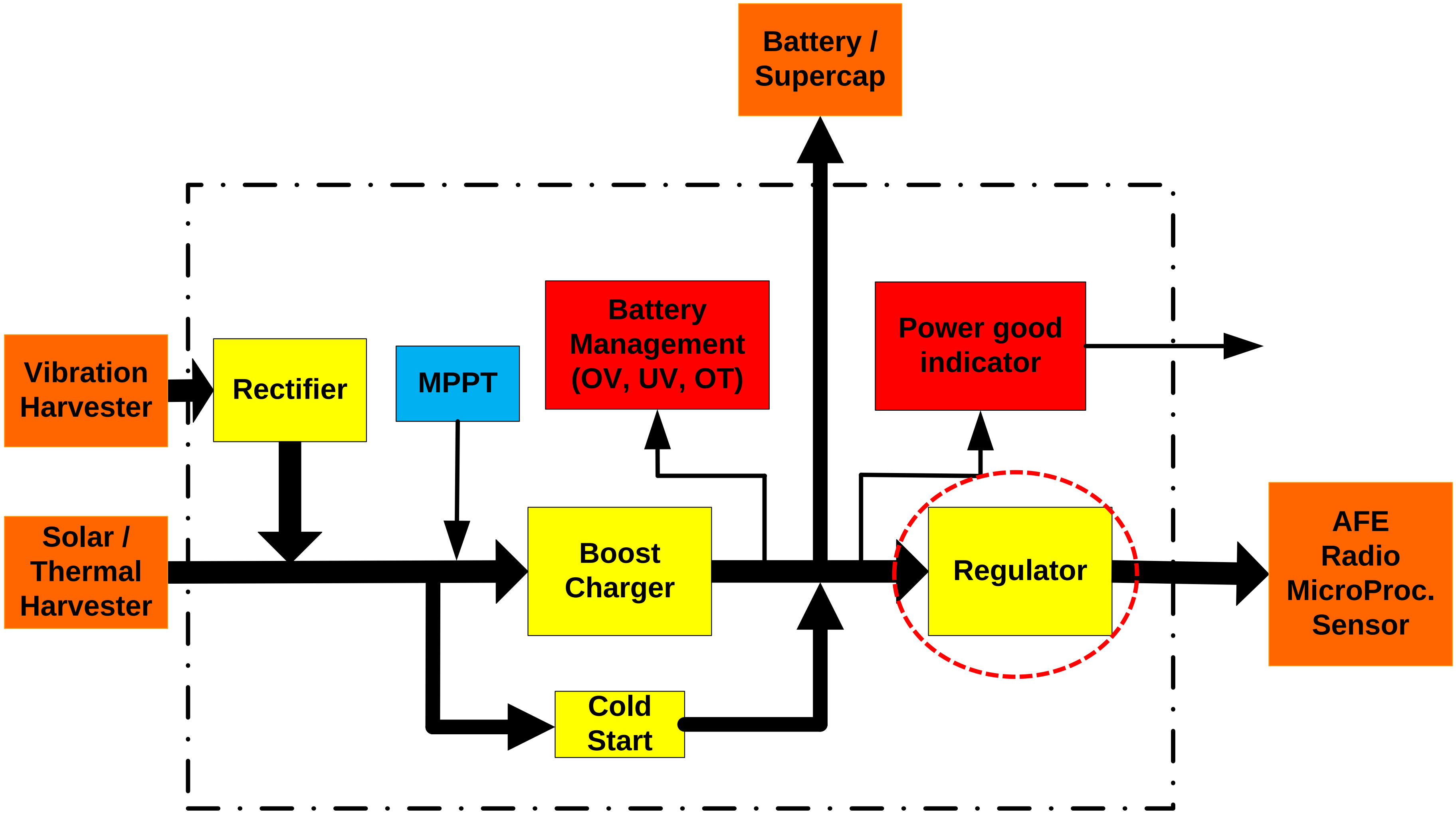
20mV Startup with Meissner Oscillator



J.M. Damaschke, IEEE Trans. on Industrial Applications, 1997

- Oscillator frequency set by L_{sec} and C_{gs}
- Loop gain
  - Magnitude condition satisfied by transformer(N ~ 20-100)
  - Phase: 180° by common-source amplifier, 180° by transformer connection
- LTC3108, ECT310 use similar technique

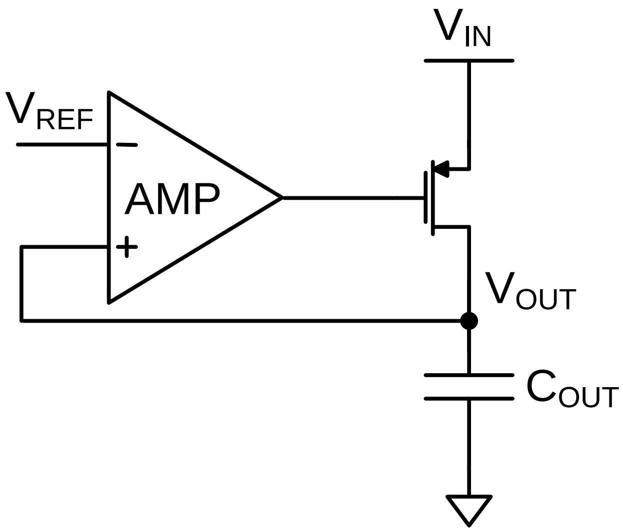
Regulator



Present stored energy as a regulated supply to load circuits

DC-DC Converter Topologies

	Linear (LDO) Regulators		
Fully integrated	√		
High efficiency	X		
Voltage Scalability	√		



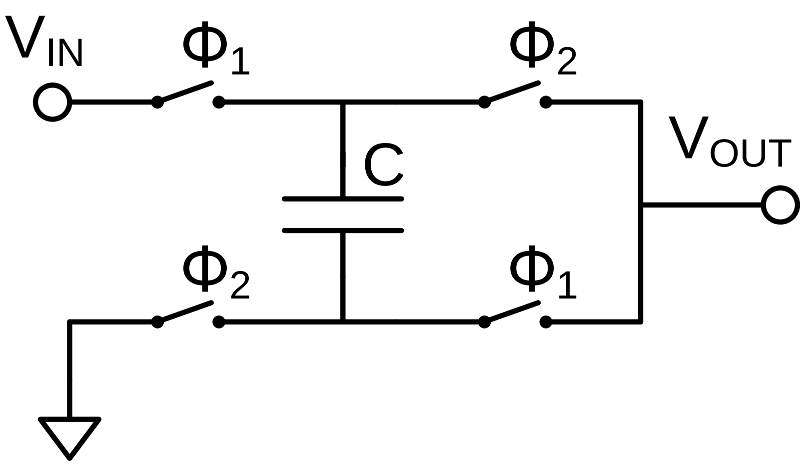
- Linear loss in efficiency
- Compact and easy to control

$$\eta = \frac{V_{OUT}}{V_{IN}}$$

M. Al-Shyoukh et al., "A Transient Enhanced Low-Quiescent Current Low-Dropout Regulator with Buffer Impedance Attenuation" IEEE JSSC, Aug 2007

DC-DC Converter Topologies

	Linear (LDO) Regulators	Switched Capacitor Converters	
Fully integrated	√	√	
High efficiency	X	√	
Voltage Scalability	√	X	

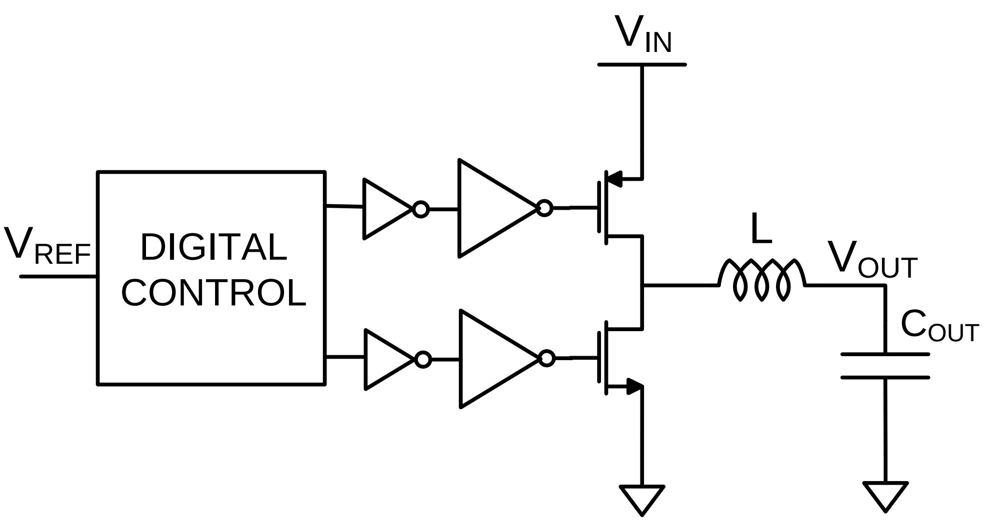


- Maintaining efficiency across load voltages is difficult
- Output current capability is limited

1) *Y. Ramadass et al., "A 0.16mm² Completely On-Chip Switched-Capacitor DC-DC Converter Using Digital Capacitance Modulation for LDO Replacement in 45nm CMOS ," IEEE ISSSC, 2010*
2) *Michael Seeman et al., "A Comparative Analysis of Switched-Capacitor and Inductor-Based DC-DC Conversion Technologies," Control and Modeling for Power Electronics, 2010*

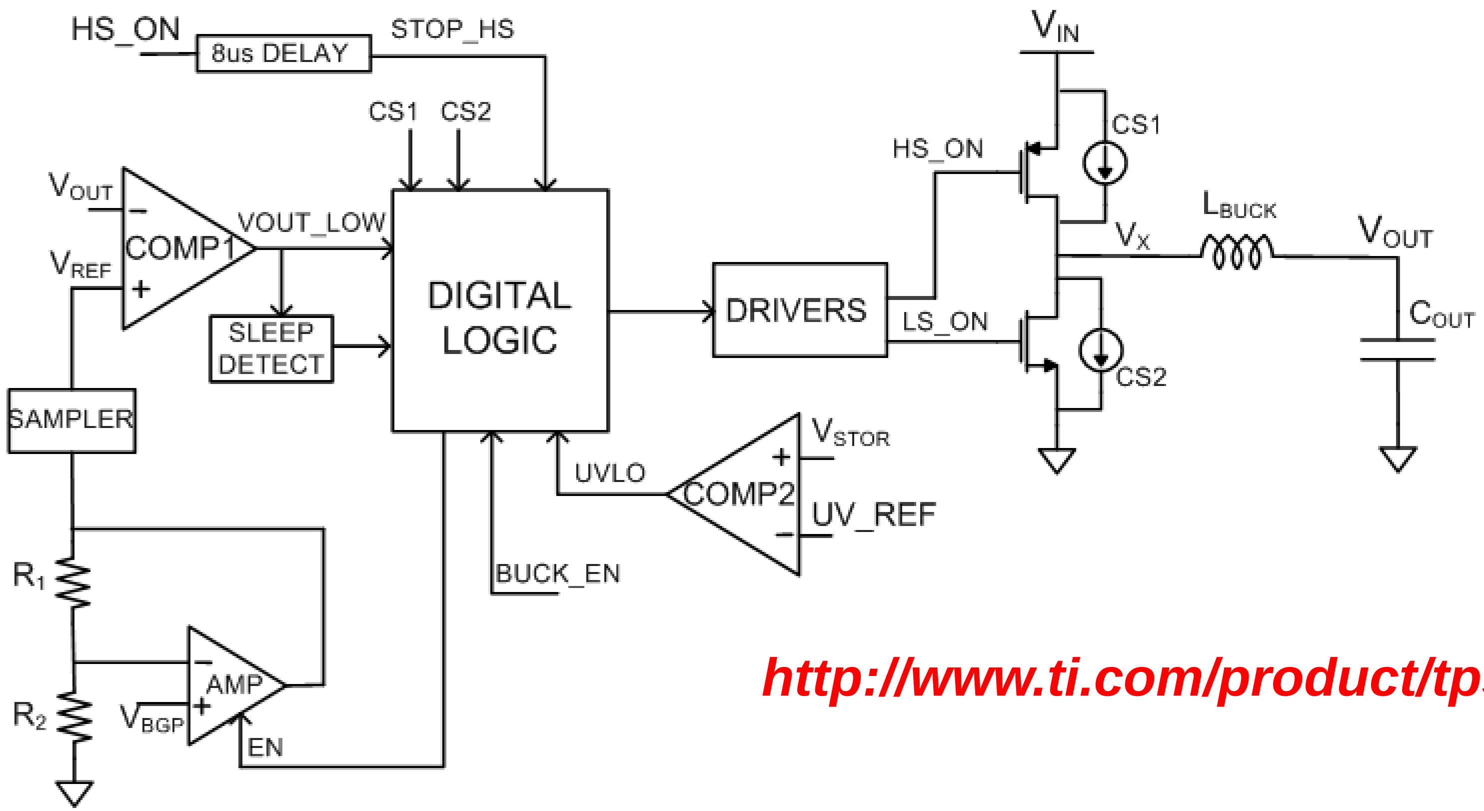
DC-DC Converter Topologies

	Linear (LDO) Regulators	Switched Capacitor Converters	Inductor-based Switching Converters
Fully integrated	√	√	X
High efficiency	X	√	√√
Voltage Scalability	√	X	√



- Needs an external inductor
- Can achieve very high efficiency
- Wide range of output voltages

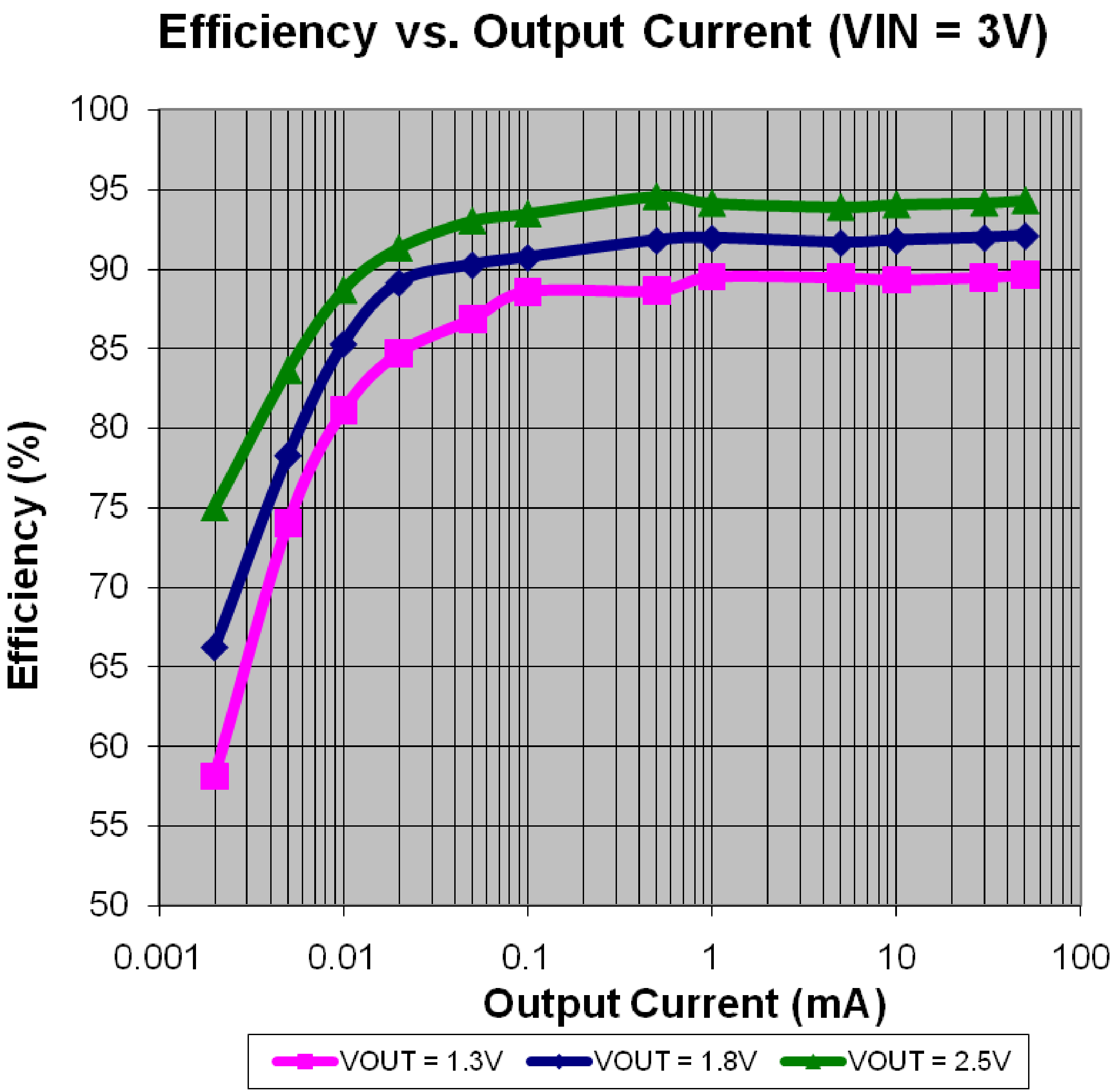
TPS62736 Buck Converter Architecture



http://www.ti.com/product/tps62736

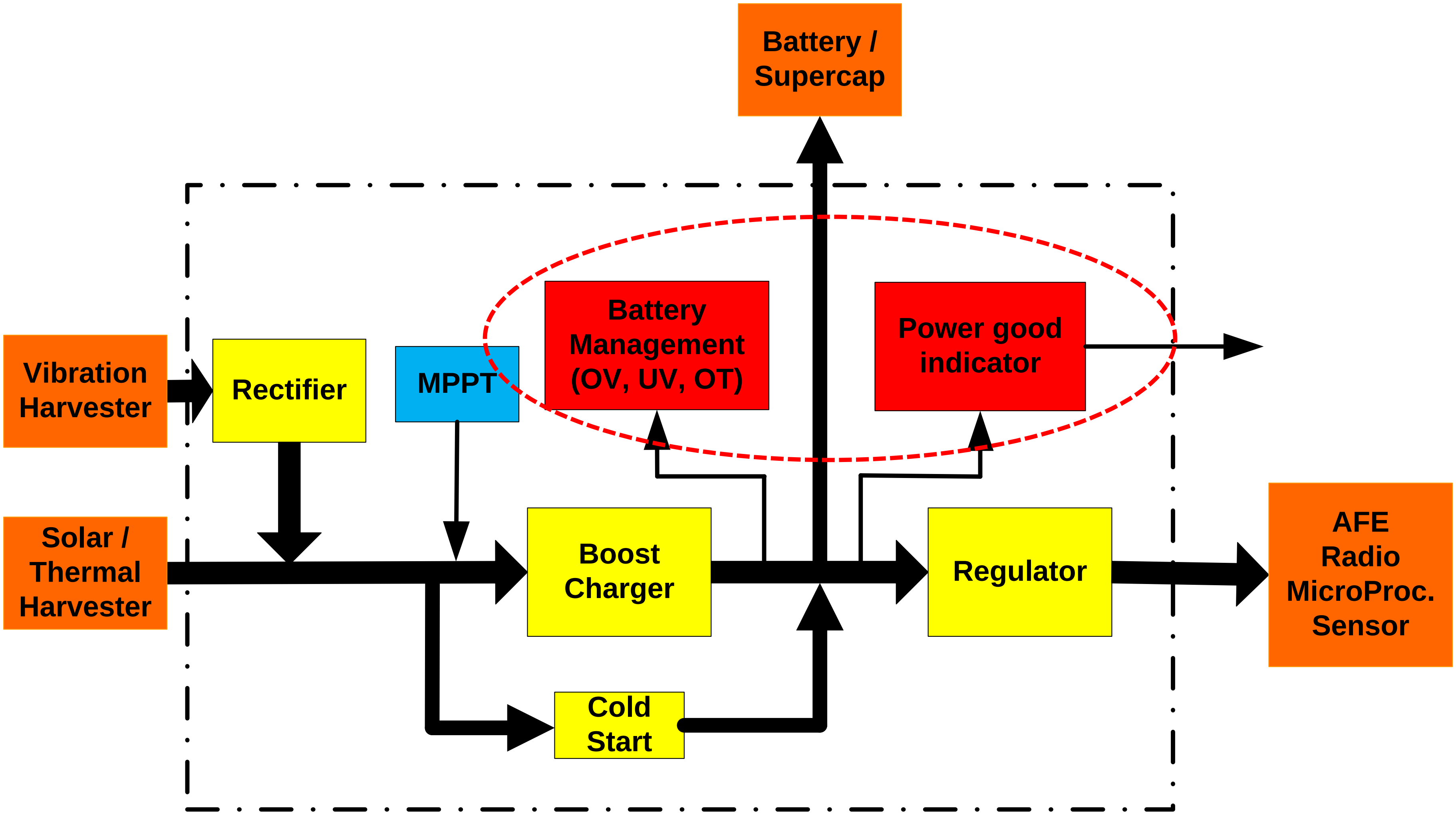
- Main comparator detects if $V_{OUT} < V_{REF}$ to enable converter
- COMP2 detects UV condition to turn off buck
- Sleep detect block to reduce IQ

TPS62736 Buck Converter Efficiency



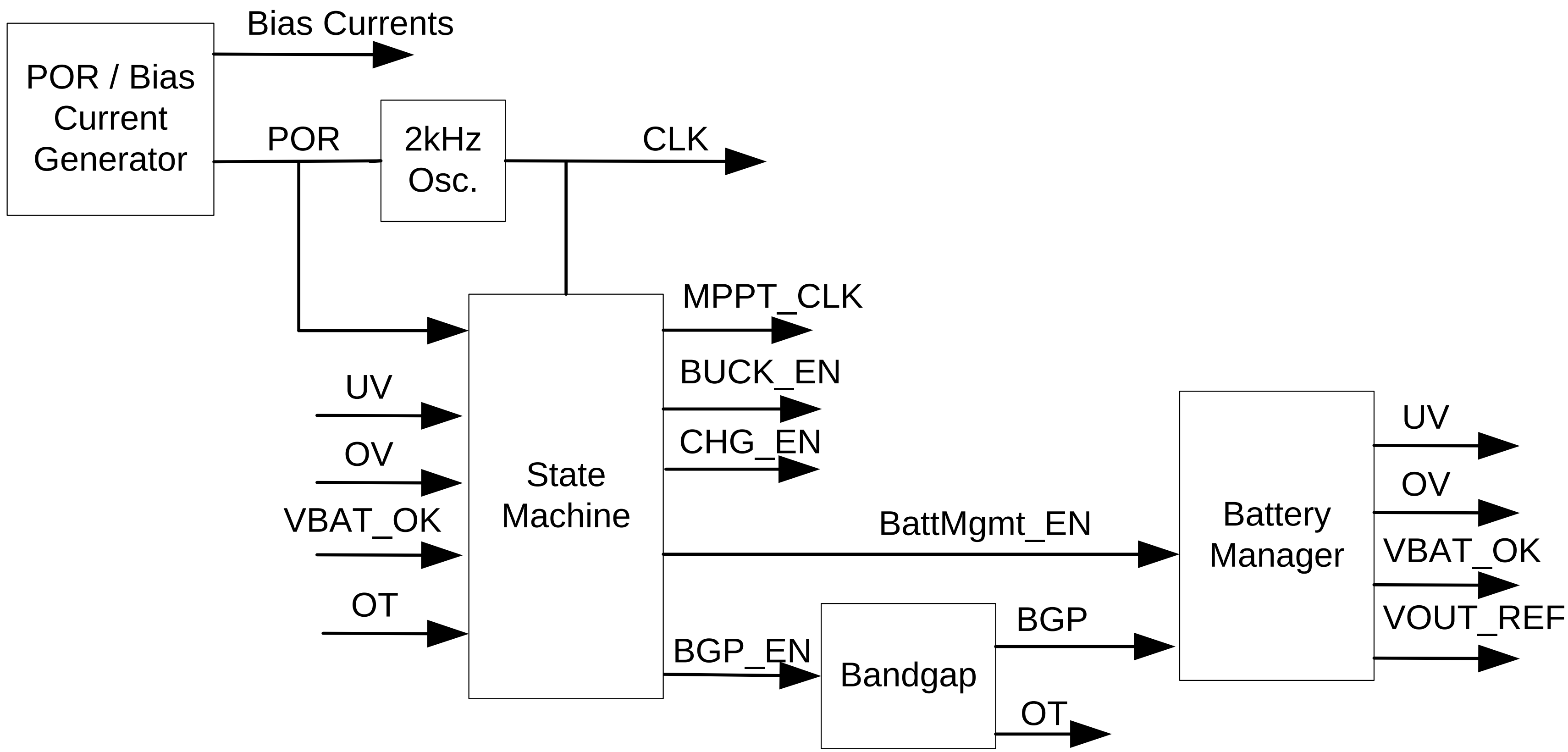
- Maintains constant efficiency from 20µA to 50mA
- >80% down to 10µA
- IQ = 360nA

Battery Management and Peripherals



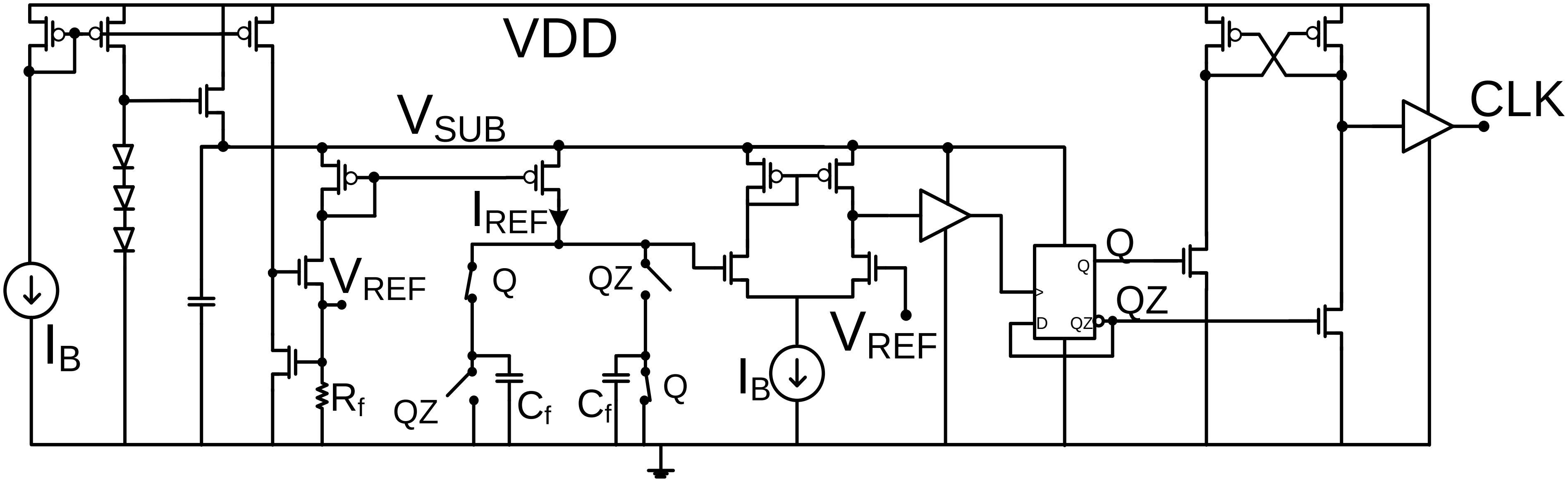
Protect the storage element, manage the IC and indicate level of stored energy

BQ25570 Essential Peripheral Circuits



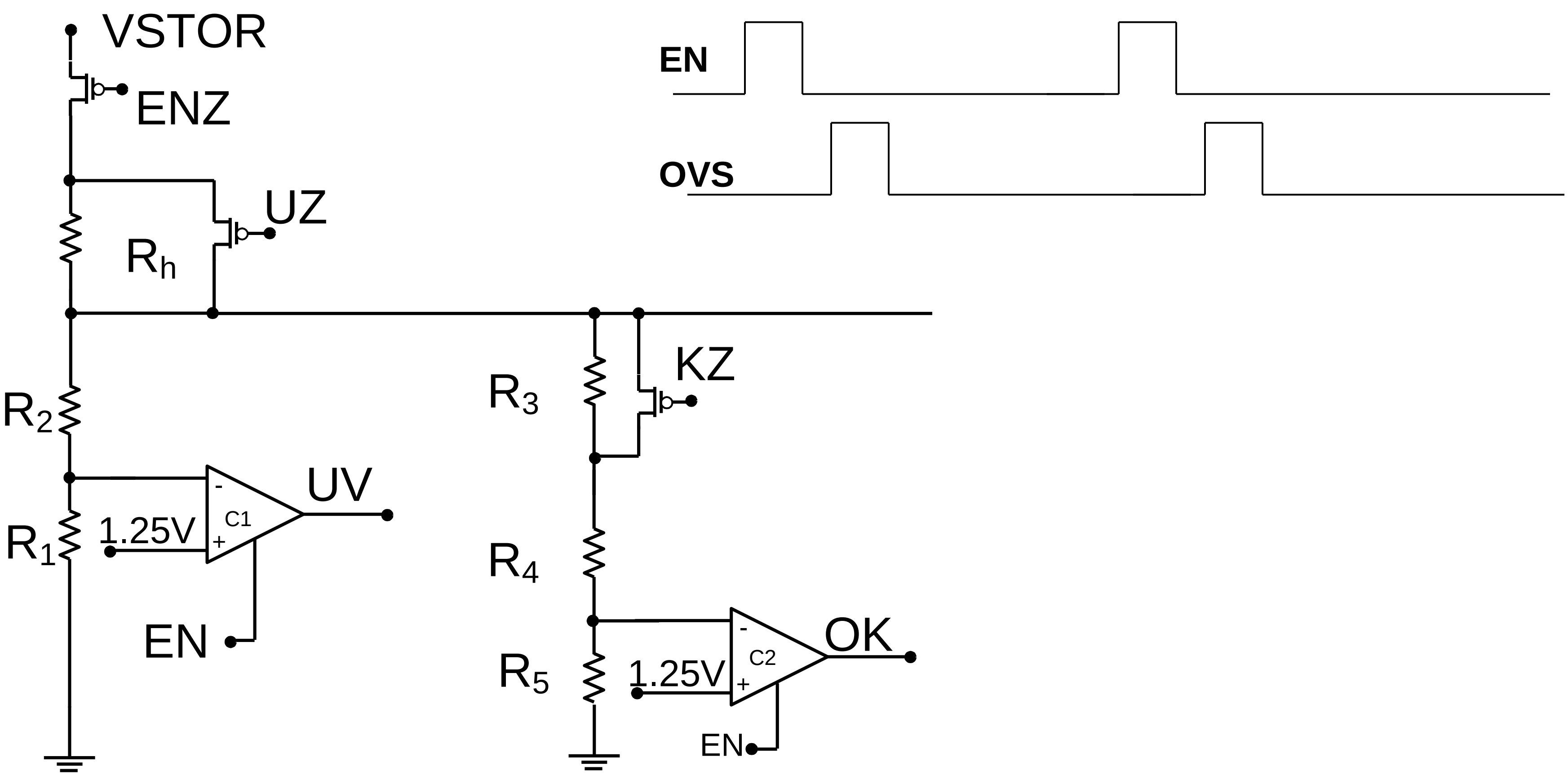
- All circuits run of VSTOR
- Perform essential startup and general maintenance of IC

Main Oscillator



- Relaxation oscillator frequency ~ 2kHz
- Sub-regulation reduces quiescent current
- **IQ = 50nA** @ 27C and 100nA across temperature

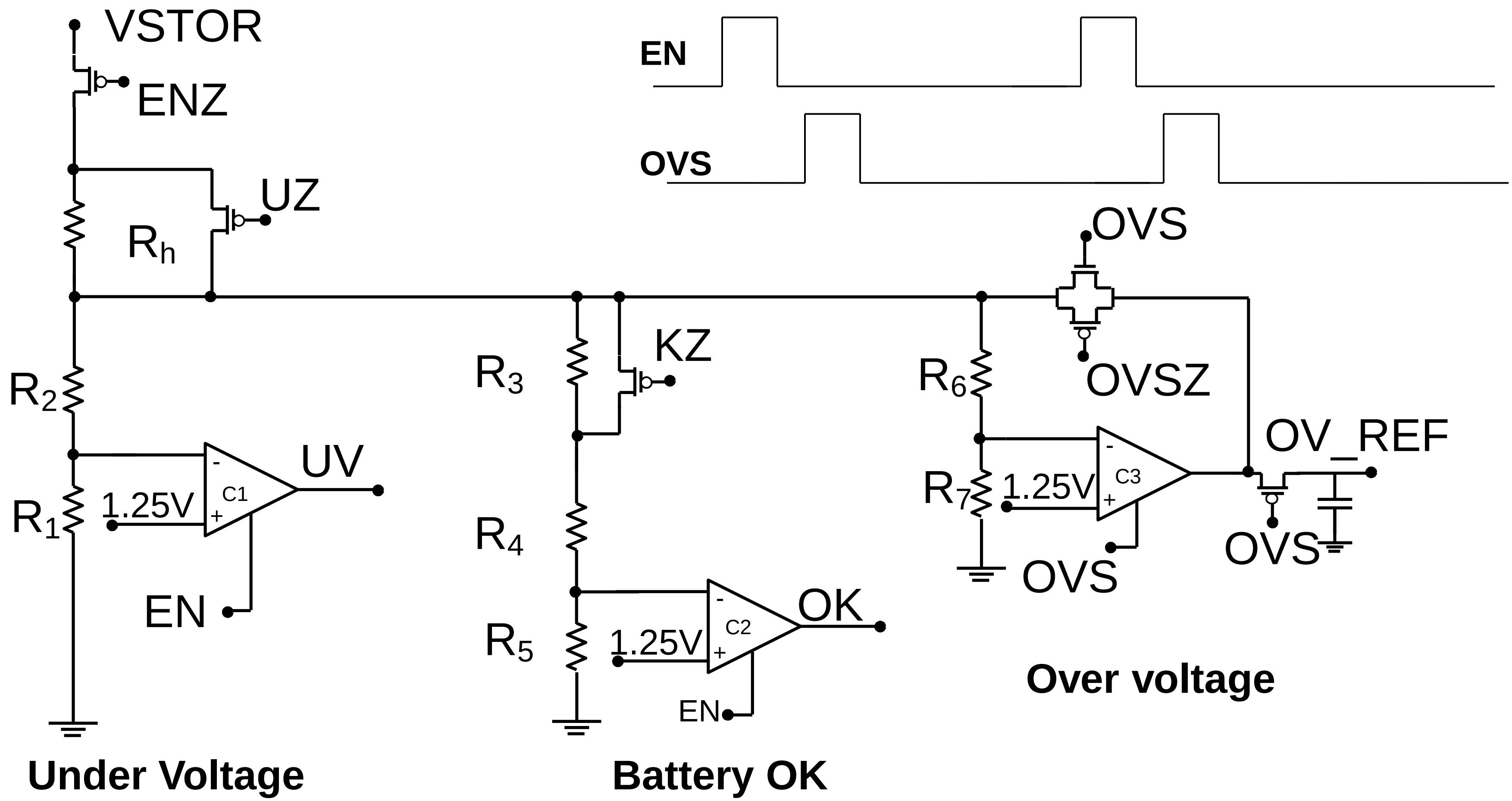
Battery Mgmt. Architecture



Under Voltage **Battery OK**

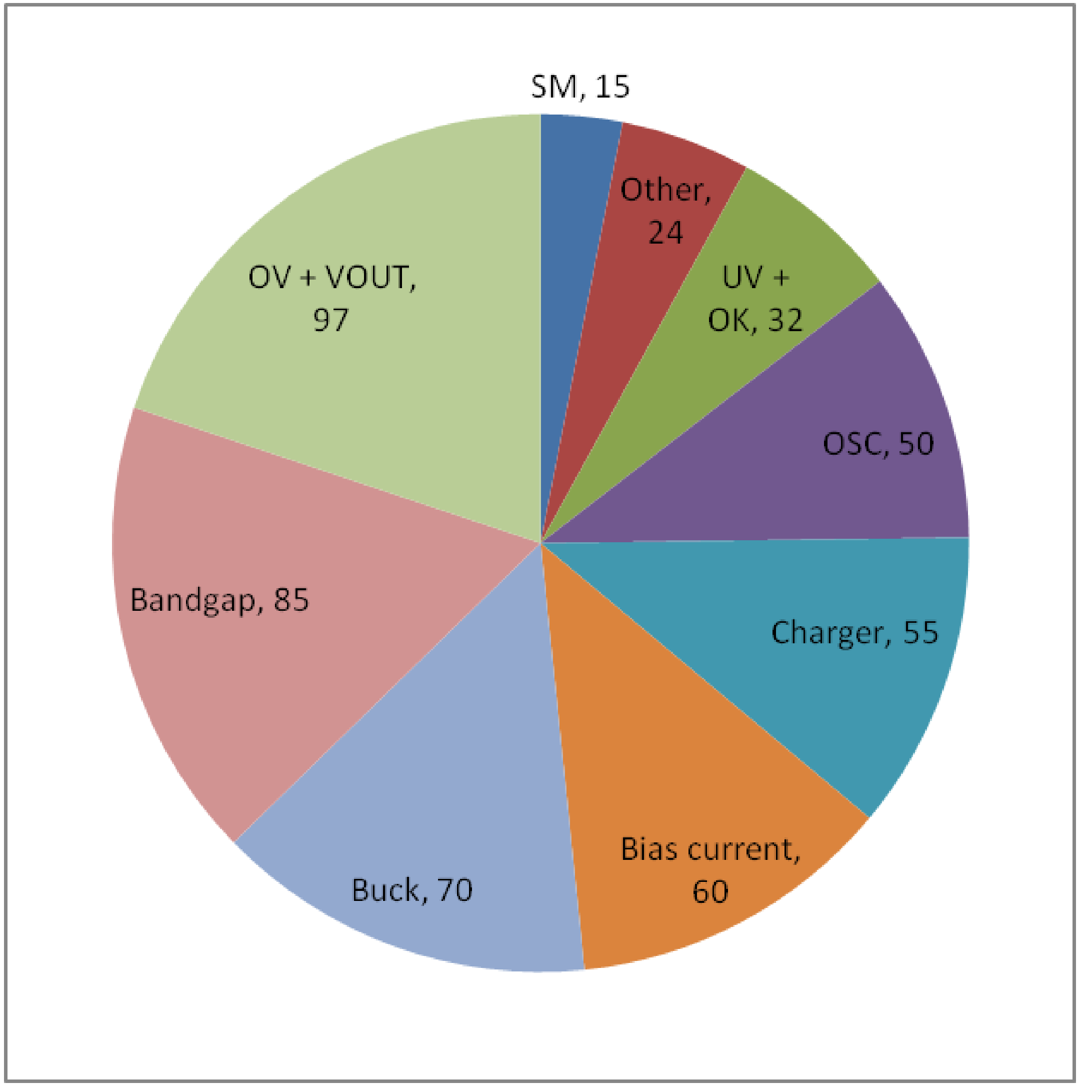
- Resistor programmable **UV**, **OK**, **OV**
- Cycle repeats every 64ms
- Duty cycled and sampled reference

Battery Mgmt. Architecture



- Resistor programmable **UV**, **OK**, **OV**
- Cycle repeats every 64ms
- Duty cycled and sampled reference

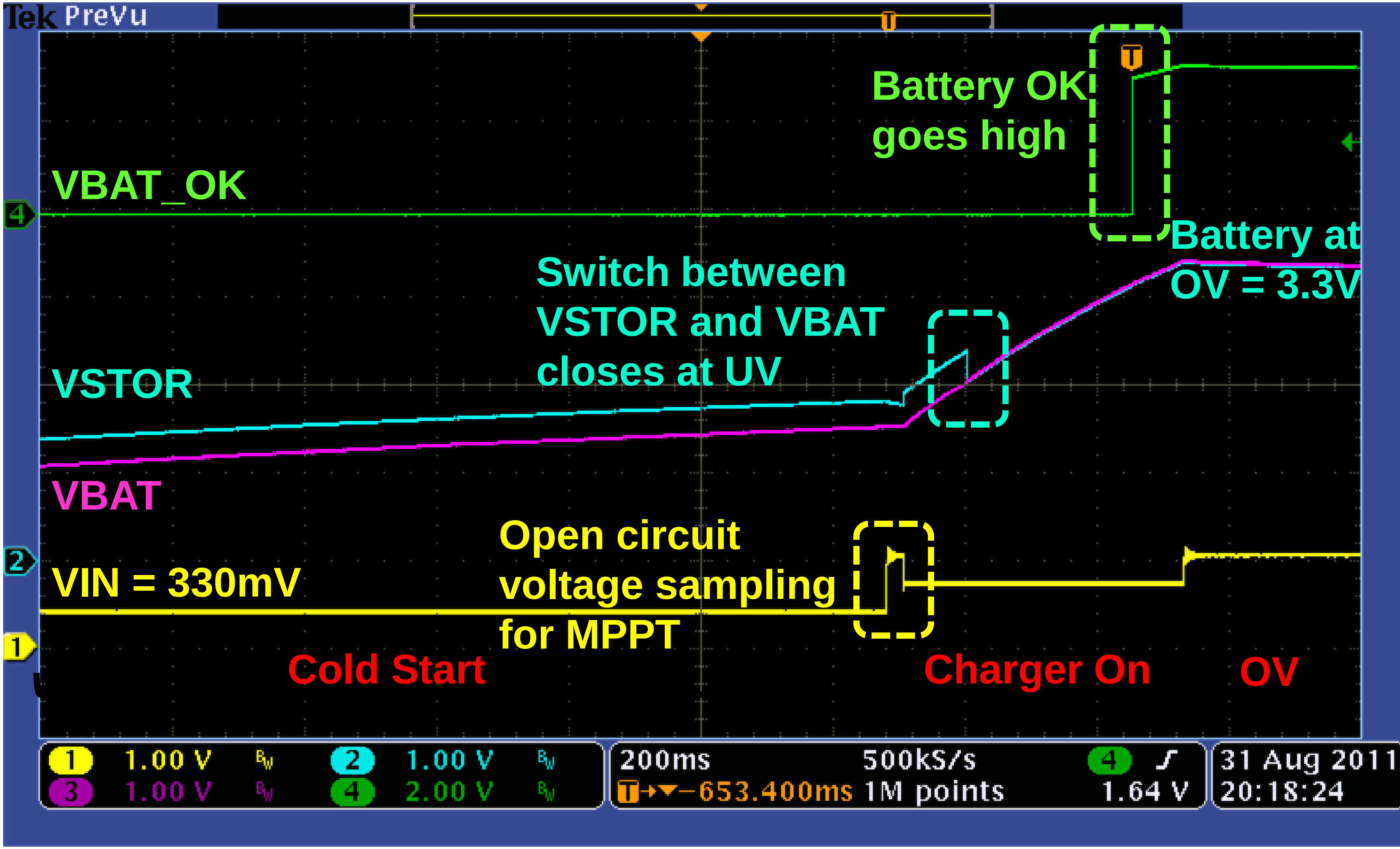
BQ25570 Quiescent Current



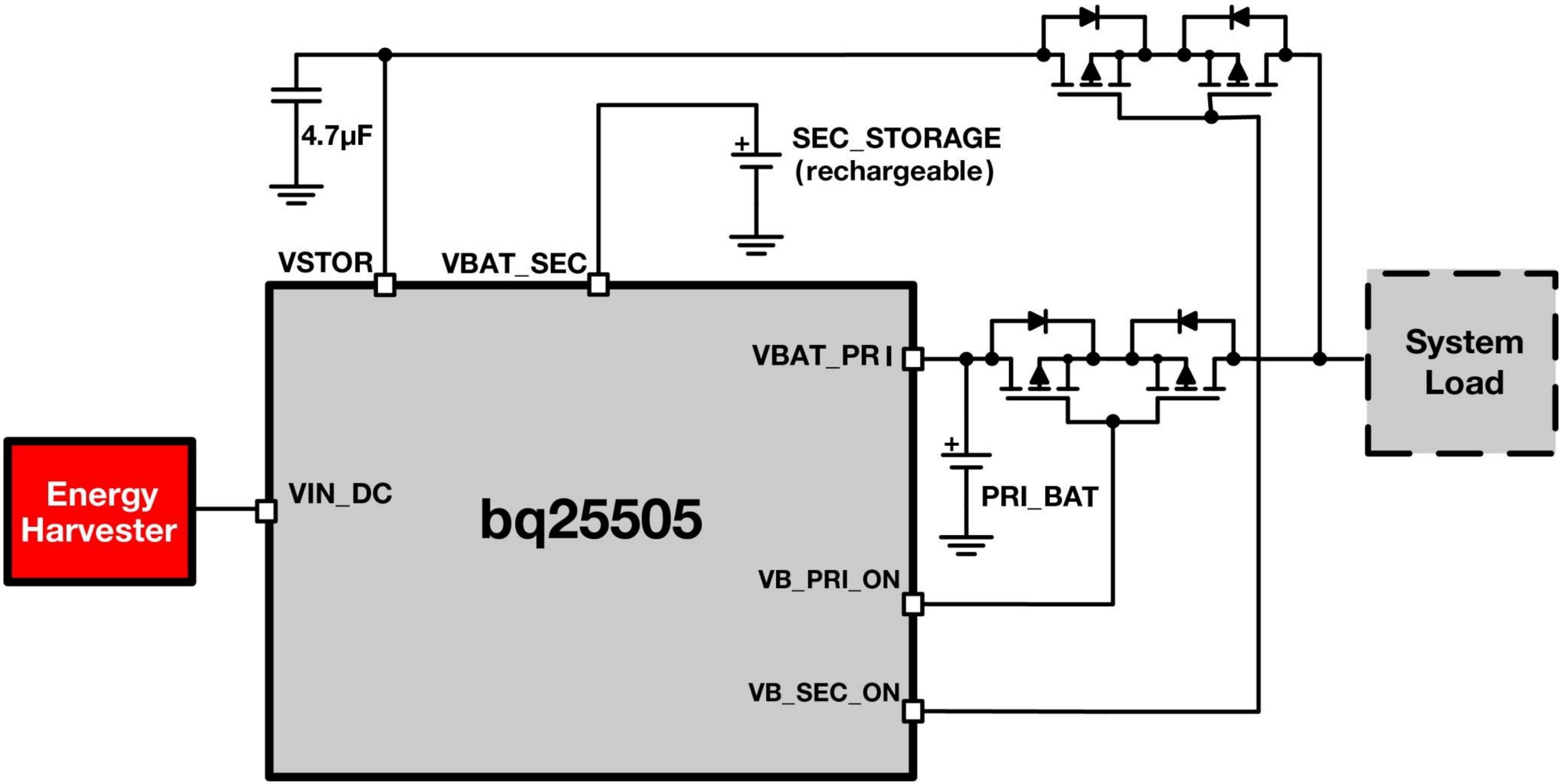
- VBAT = **3V**
- Overall Quiescent current : **480nA**
- Battery leakage below UV **= 1nA**

Currents in nA

BQ25570 System Startup



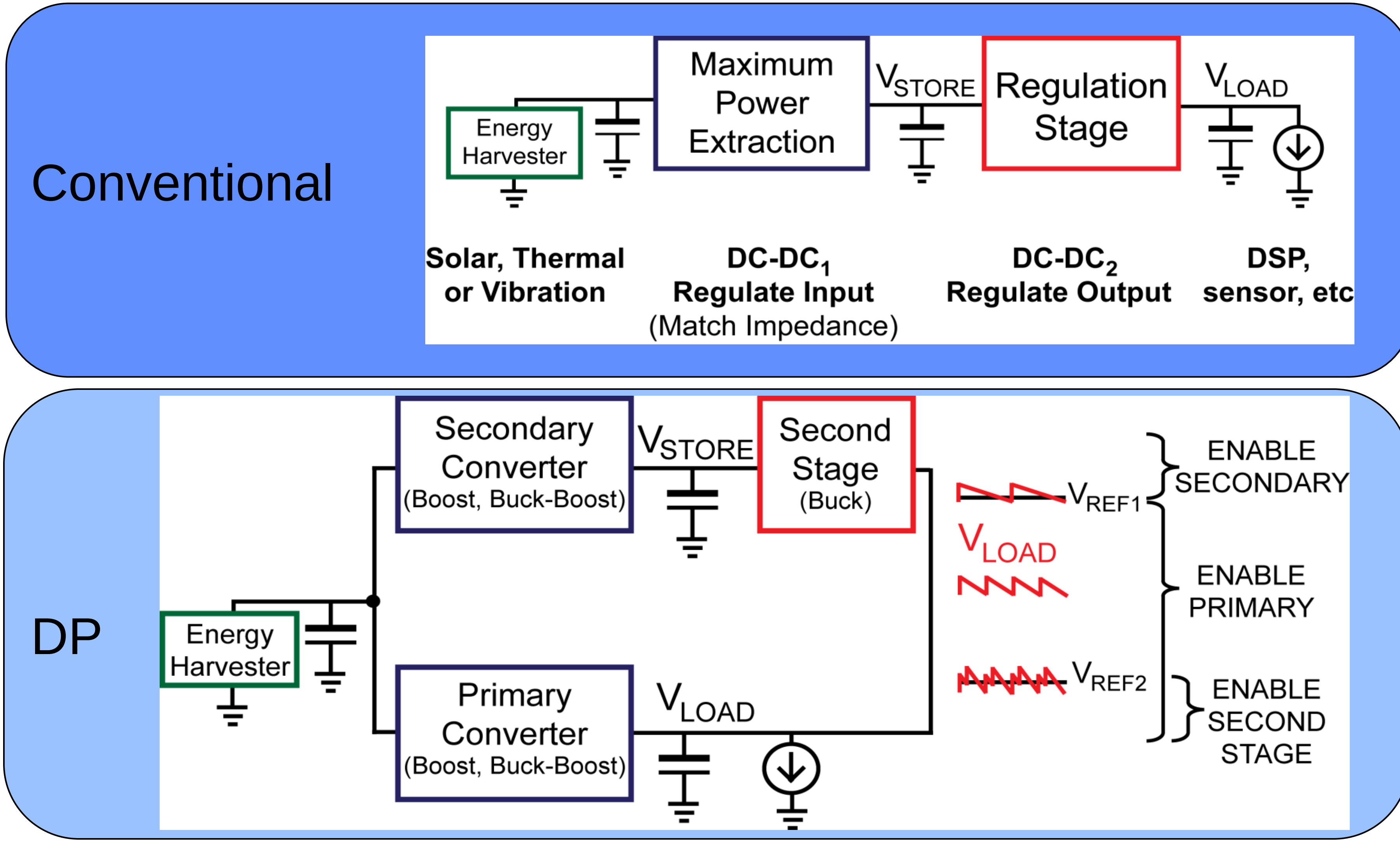
Energy Harvesting with Battery Backup



http://www.ti.com/product/bq25505

Autonomous handoff between primary and secondary storage

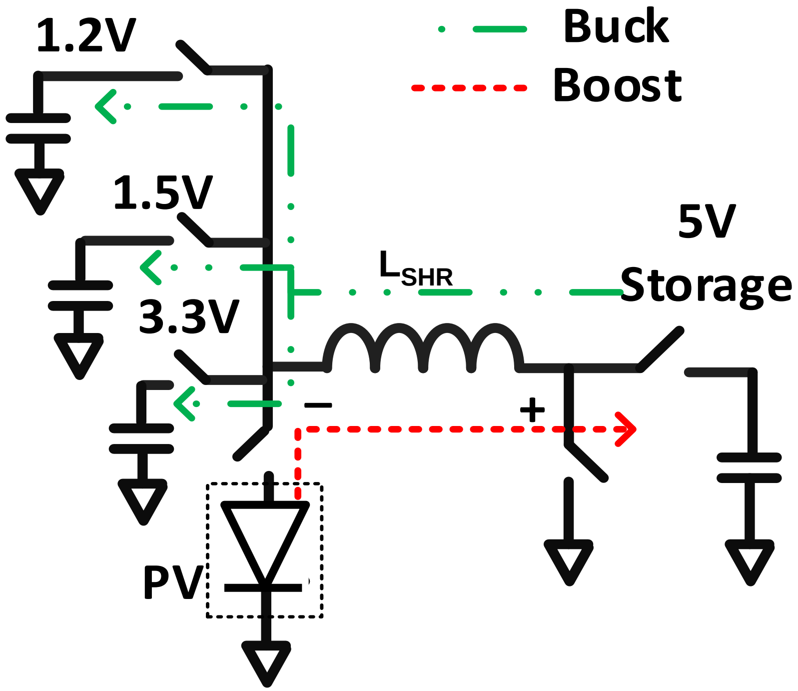
Dual-Path Energy Harvesting

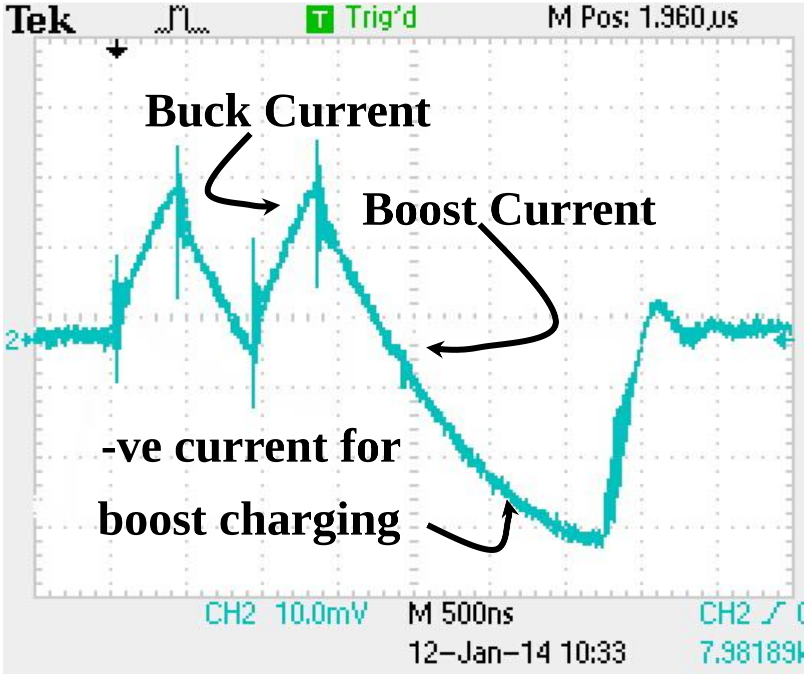


Bypassing Second Stage results in 13% peak efficiency improvement

[S.Bandyopadhyay , VLSI Symposium 2011]

Inductor Sharing

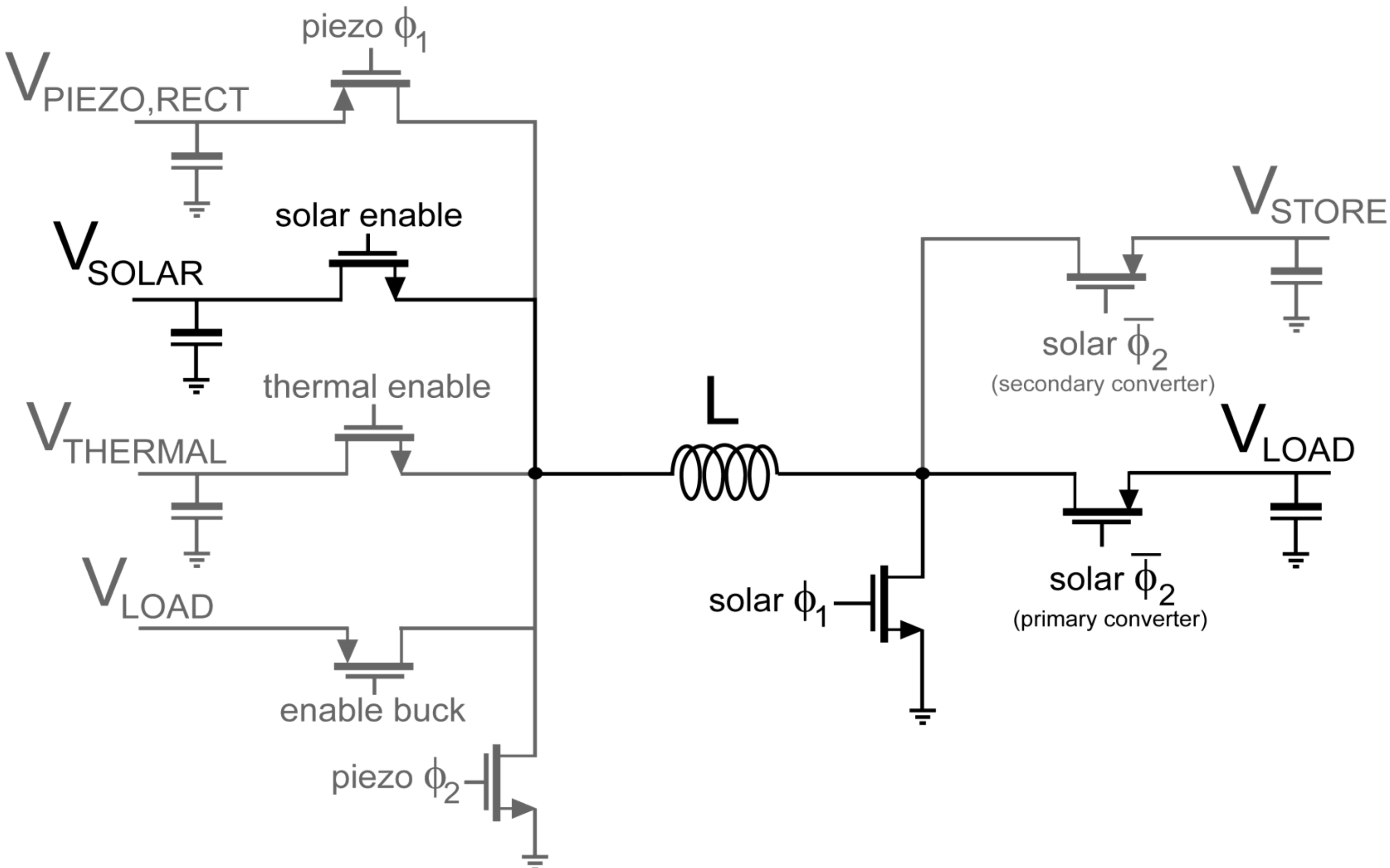




- A single inductor is used for boost conversion as well as for generating multiple regulated output voltages

[A. Shrivastava, VLSI Symposium 2014]

Energy Combining



Shared inductor minimizes board components

Summary

- Advances in circuit design techniques and architectures have made it possible for electronic systems to be completely self-powered
- Energy harvesting sources differ in characteristics from conventional batteries requiring specialized interface circuits
- Optimized energy processing circuits are crucial to manage the ultra-low power levels output by energy harvesters
- Holistic optimization of the complete system from the energy sources to the load circuits is key to building a successful IoT system